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Technical Report R485

STATIC AND DYNAMIC PROPERTIES OF FIRE-RESISTANT WOODEN STRUCTURAL ELEMENTS

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STATIC AND DYNAMIC PROPERTIES OF FIRE-RESISTANT WOODEN STRUCTURAL ELEMENTS

Technical Report R-485

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by

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ABSTRACT

A series of treated and untreated laminated Douglas fir beams and plywood panels were subjected to static and dynamic loads to study the effects of pressure-impregnation with fire-retardant chemicals on the mechanical properties of wood and to extend the existing knowledge of the dynamic properties of wood.

Results from the beam tests indicate that designs should be based on use under wet conditions when large timbers are to be pressure-impregnated with fire-retardant chemicals; this is because of the hygroscopic nature of treated lumber. It was also found that the allowable static design load can be applied dynamically without damage to the beam. Ultimate resistance of dry untreated beams to dynamic loads was about 1.6 times the allowable design load for dry wood; for treated beams, the ultimate resistance to dynamic loads was about 1.4 times the allowable design load for wet lumber.

Results from the plywood shear tests indicate that fire-retardant treatments reduce the mechanical properties of plywood in shear and that the reduction is proportional to the amount of salt retained in the wood.

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The Laboratory invites comment on this report, particularly on the results obtained by those who have applied the information.

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INTRODUCTION

There have been serious objections to the use of wood as a construction material, especially in congested areas such as cities, because of its relatively low ignition temperature and the ease with which it burns. Attempts to render wood fire-resistant have been successful, and the prominent building codes now contain provisions for the use of fire-retardant processed wood.

A factor that has created some concern, however, is the possibility that fire-retardant chemicals or the impregnation process, or a combination of both, might have adverse effects on certain strength properties of the wood. Voluminous data are available on the strength properties of wood, but not on wood treated with preservatives.

Previous investigations[1] have shown a significant reduction in many of the mechanical properties of wood when it has been pressure-impregnated with fire-retardant chemicals. The most adversely affected properties were toughness (a measure of the energy absorbed up to the point of failure) in beams[2, 3] and shear resistance in plywood.[4] Among the factors contributing to reduced strengths in treated wood were the incising process (punching small holes in the wood to aid chemical penetration) and kiln drying after treatment.[1, 16, 17]

This study was initiated to determine the effects of pressure-impregnation with fire-retardant chemicals on the mechanical properties of laminated Douglas fir beams and plywood subjected to static and dynamic loading. Full-cell pressure treatment with the fire-retardant NON-COM was employed in accordance with Military Specification MIL-F-19140A. The lumber was not incised before treatment; this precluded strength reduction resulting from the perforations. The lumber was allowed to air-dry to minimize checking and cracking from forced drying. This procedure was intended to provide approximate equilibrium moisture-content values for large timbers and plywood under desorbing moisture conditions rather than the absorbing moisture conditions resulting after kiln drying.

Twelve laminated Douglas fir beams 15 feet long and sixteen 1/2-inch Douglas fir plywood sheets 14 inches square were tested under static and dynamic loading conditions. The objectives of the test program were the following:

1. To study the effects of pressure-impregnation with fire-retardant chemicals on the strength of laminated structural timbers in flexure and on plywood in shear.

2. To extend existing knowledge of the dynamic properties of wooden structural elements.

3. To provide information which would aid in the formulation of design criteria applicable to fire-resistant structures.

In the following sections the beam investigations are presented first. The test program is described, and the results are presented and discussed. A similar procedure is followed for the second phase of the study on plywood. A general discussion of results including major findings, limitations of the program, and accuracy of results is included to summarize the investigation. Conclusions and design recommendations are then presented.

LAMINATED BEAMS

Laminated wooden beams differ from solid members in that they are fabricated from a number of select planks with the grain running in the same direction, and are fastened together to permit the assembly to serve in the same way as a solid member. One of the advantages of laminated-wood beams is the possibility of utilizing materials of higher grade or of a stronger species in those portions of a beam that are subjected to maximum stress, permitting weaker material to be utilized in the remainder of the member. Another advantage is that any treatment of the wood may be performed on the individual planks before laminating and thereby eliminating the need for large treatment facilities.

This phase of the study is concerned with the effects of pressure-impregnation with fire-retardant chemicals on the mechanical properties of laminated structural timber beams subjected to static and dynamic loading.

Description of Beams

Twelve beams having dimensions of 7-7/8 inches wide, 13 inches deep, and 15 feet long were prepared by a local fabricator. Each beam contained nine horizontal laminations of Coast-Region Douglas fir bonded together with an exterior-type glue. The interior laminations were standard grade lumber, and the top and bottom laminations were select structural grade lumber. Allowable unit bending stress and minimum modulus of elasticity were 2,200 psi and 1,800,000 psi, respectively, for dry lumber, and 1,800 psi and 1,600,000 psi, respectively, for wet lumber. Fabrication was performed according to the American Institute of Timber Construction specifications.[5]

After fabrication, the beams were shipped to a commercial treatment plant where six beams were pressure-impregnated with fire-retardant chemicals. Treatment resulted in an approximate 85% increase in weight and 5% increase in volume. There was some tendency for normally tight surface knots to become loose as a result of the treatment process. Depth of penetration of the chemicals was determined after the beams were tested by cutting a section from the beam near midspan and drying it at 217°F for 48 hours. The treated portion of the cross section turned a dark brown. Chemical indicators were applied to the cross section also, but these indicators were

so sensitive to the presence of the fire-retardant salts that sawdust from the treated portions contaminated the entire cross section, resulting in a false test. The depth of penetration of chemicals is shown in Figure D-1 in Appendix D.

After the beams were chemically treated, they were marked for identification, weighed, and inspected for knots, checks, glue-line separation, and other defects; the beams were then stored in a protected environment at approximately 50% relative humidity and at temperatures ranging from 45°F to 75°F. Figure 1 shows the drying rate of the treated beams while in storage. The curves were constructed from calculations based on the total weight of the beams at any given day and the weight of oven-dried sections cut from the beams after all the tests were completed. The moisture content is plotted as a percentage of the oven-dried wood.

Treated beams are identified as T1 through T6 and untreated beams as U1 through U6.

Test Equipment

All of the beams, either statically or dynamically loaded, were tested in the NCEL blast simulator[6] shown in Figure 2. The simulator is capable of applying uniformly distributed loads (gas pressure) up to 200 psi. A tank filled with air by a compressor is bled into the simulator to apply static loads.

Dynamic loads are applied by detonating a high explosive (Primacord) within a firing tube in the simulator. The peak dynamic pressure is determined by the length of Primacord; the decay time is controlled by opening a series of valves which release the gases to the atmosphere. The rise time of the load is approximately 2 to 4 milliseconds, depending on the location of the specimen in the explosive chamber.

Instrumentation

Instrumentation was located as shown in Figure 3. Applied load was measured with 100-psi Statham pressure cells. Each support reaction was measured with a 60,000-pound-capacity Kulite-Bytrex load cell mounted between plates of each support cast (Figure 4). Midspan motion was measured with a 6-inch Bourns potentiometer and a 500-g Statham accelerometer. Midspan deflection was also measured with the rotating drum gage shown in Figure 5. The drum, which rotates at a constant speed, has a sheet of vellum attached that records the motion of a pencil attached to the beam.

Longitudinal strains in the top and bottom laminations were measured with type A5-1, SR-4 electric strain gages. Strains in the inner laminations were measured with a pair of type A5-1, SR-4 electric strain gages bonded to opposite faces of the beam at the same elevation and wired to opposite arms of a Wheatstone bridge. Dummy gages bonded to Douglas fir blocks were wired to complete the bridge. To prevent the gages from contacting the sides of the simulator, a 1/8-inch-deep section was routed from the beam, and the gages were placed flush with the surface. SR-4 cement was used for bonding the gages to the wood. A Budd model A-110 digital strain indicator was used to record the test data from the static tests.

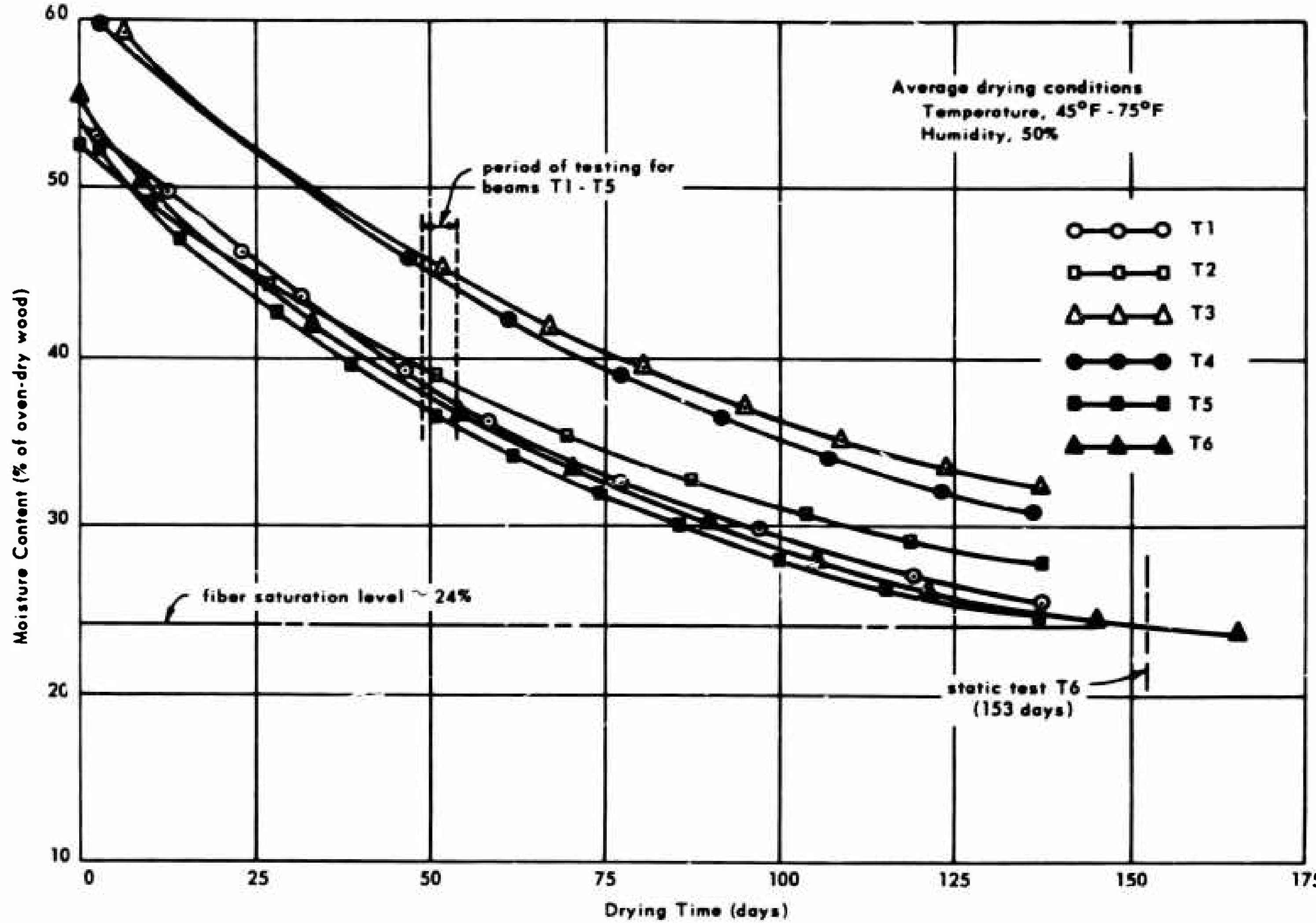


Figure 1. Moisture content versus drying time for treated beams.

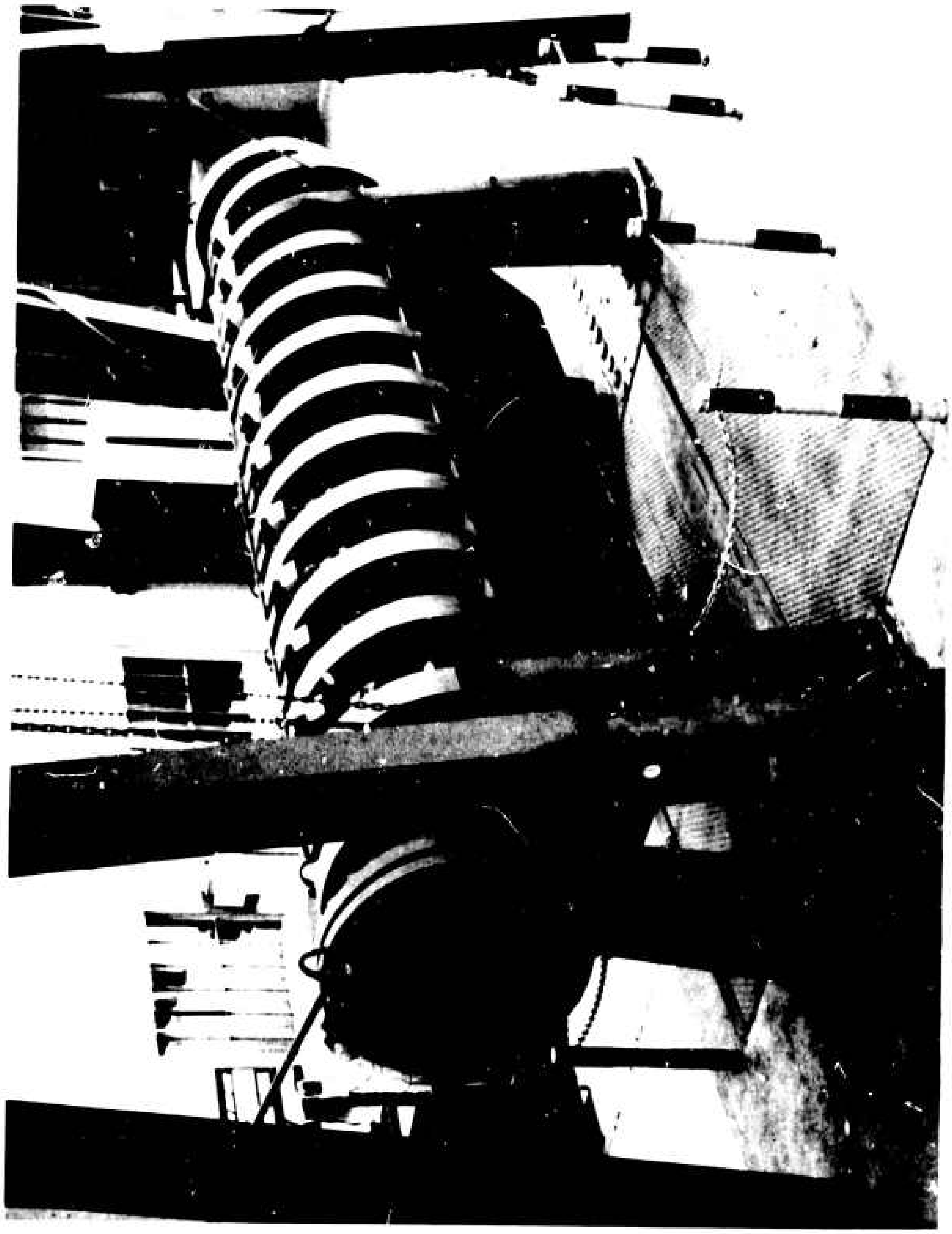
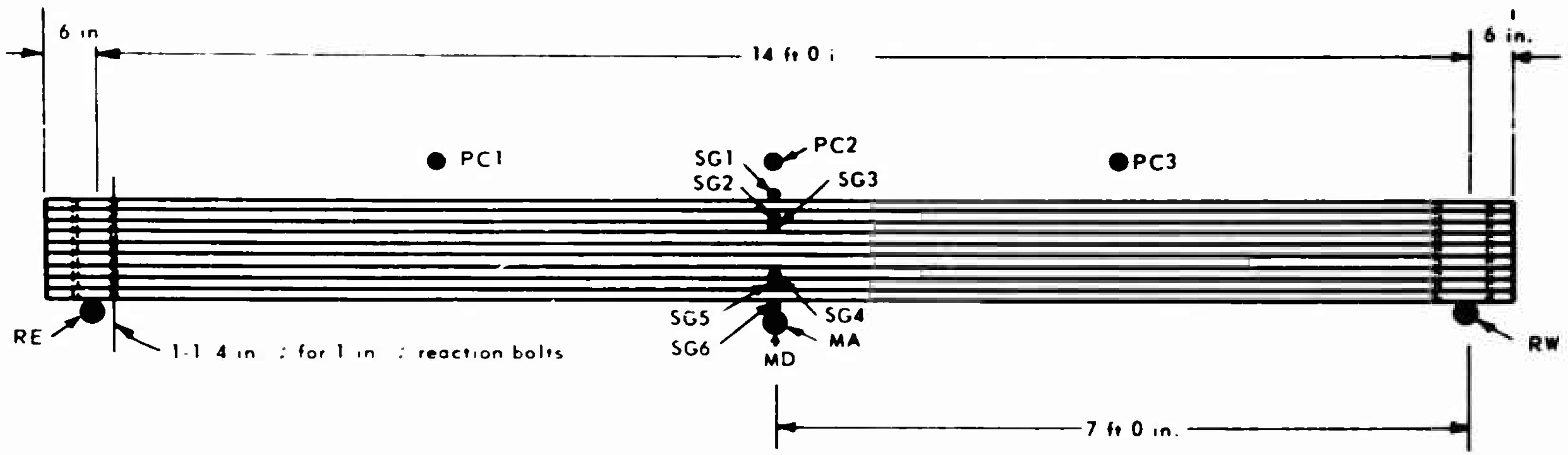
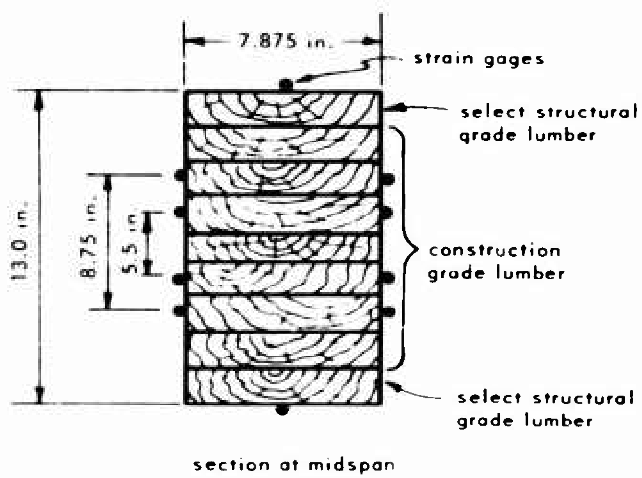


Figure 2. NCEL blast simulator.





Mark	Measurement
SG1 - SG6	strain
MA	midspan acceleration
MD	midspan deflection
PC1, PC2, PC3	pressure
RE, RW	reaction

Figure 3. Beam details and instrumentation.

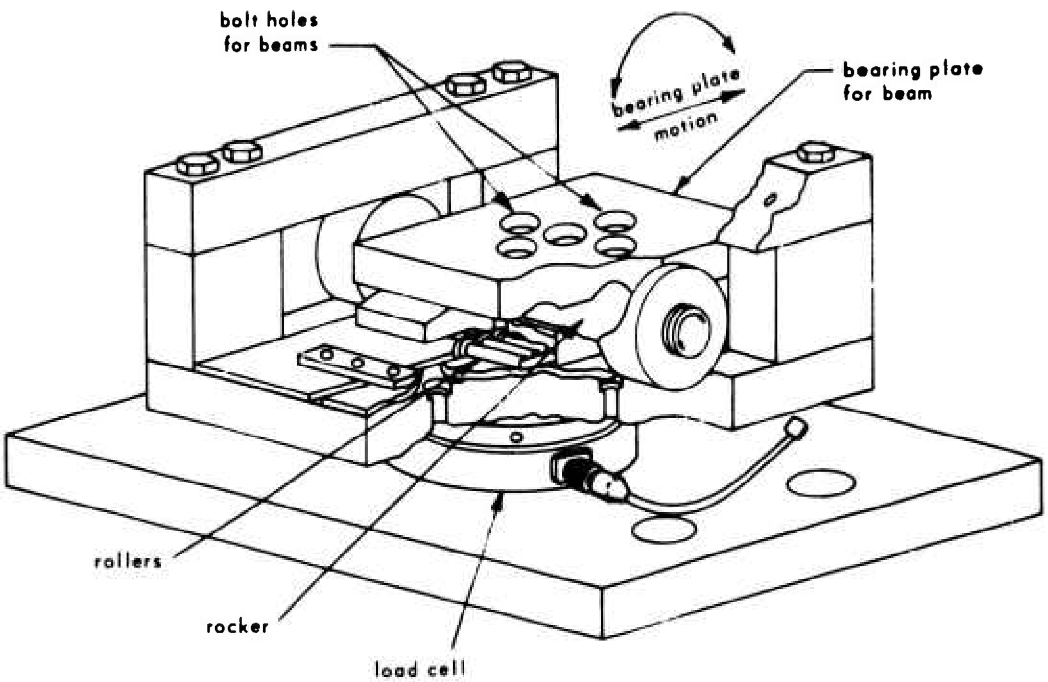


Figure 4. Support configuration.

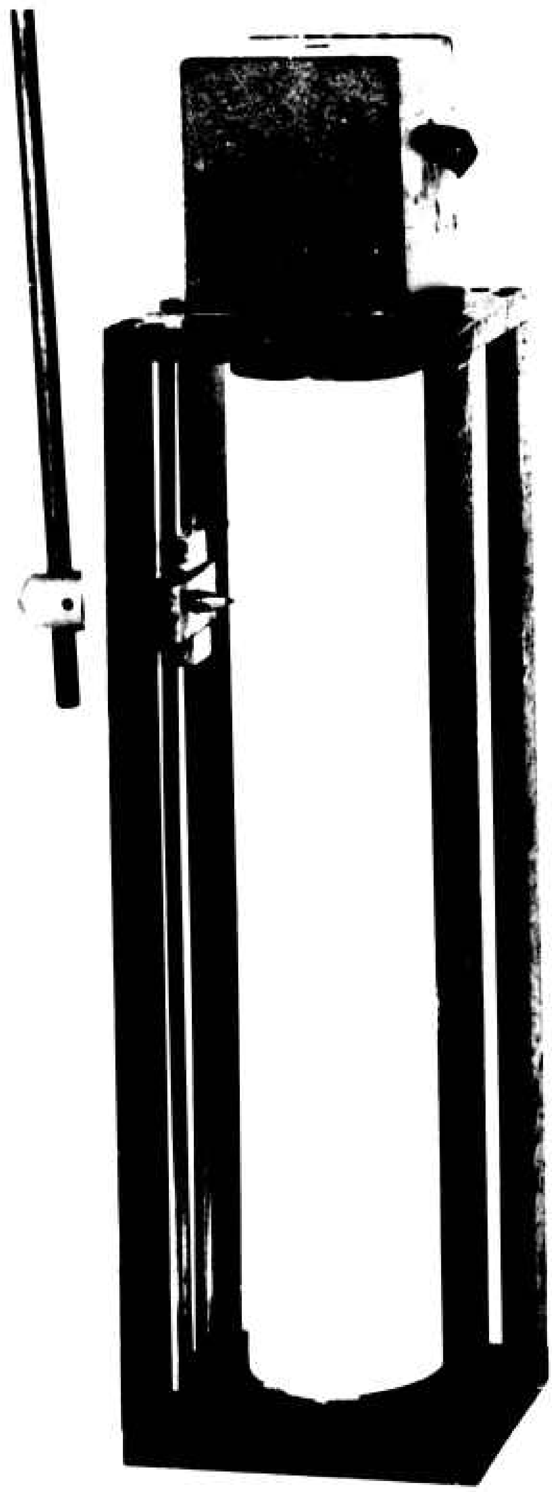


Figure 5. Rotating-drum deflection gage.

Dynamic test data were recorded and reduced using the data-handling complex developed for the NCEL blast simulator.[7] The system was developed for rapid, accurate, efficient, economical, and timely reduction of data recorded during dynamic tests. The complex is separated into three systems: data collection, data conversion, and data reduction. The data generated are recorded on magnetic tapes which are then converted to a visual record or to input to a computer for reduction.

Test Procedure

Preparation of a beam was the same for both static and dynamic tests. The beams were placed on the reactions and bolted securely. A sheet of Teflon was draped over the top and down the sides of the middle quarter of the beam to reduce the possibility of friction against the sidewalls of the simulator. Small dollies were placed under the beam, and the unit was rolled between the skirts of the blast simulator. The dollies were then removed, and the reactions were bolted to the concrete foundation. The bolts through the beams and into the reactions were then loosened to reduce any horizontal shear resistance offered by the bolts or the clamping effect of the tie-downs. Finally, all measuring instruments were fastened to the beam, all electrical connections were made, and a strip of neoprene was placed over the top of the beam to seal the chamber. A beam ready for testing is shown schematically in Figure 6.

Static Tests. Beams U3, U4, T1, and T6 were loaded statically to failure under uniform pressure; the remaining beams were subjected to blast loading. Beam U3 was subjected to blast loading twice without apparent damage and was then loaded statically to failure.

In the static tests, the beams were uniformly loaded by introducing compressed air into the pressure chamber of the blast simulator. The pressure level was monitored from an Emery pressure gage (375 psi capacity). Loading was in 5-psi increments up to 30 psi; thereafter, the pressure increments were 2 psi until the ultimate resistance of the beam was overcome. Each static test required approximately 15 minutes to perform.

Prior to loading, the natural frequency of the beams was determined by displacing the beam and releasing it suddenly. The resulting free vibration, detected by strain gages and other transducers, was recorded.

Dynamic Tests. In the dynamic tests, the beams were loaded by detonating an explosive charge in the pressure chamber. After a beam was in place, the simulator was loaded with the proper explosive charge for the desired pressure and sealed. Blasting caps were then inserted and wired to the master-control circuit. The master-control unit was then unlocked, allowing a switch to be closed which starts the firing procedure. When the switch is closed, a preset electronic programmer starts the recording equipment, automatically detonates the explosive charge, and shuts off the recording equipment. For these tests, the air vents were kept closed to simulate a step-pulse-load characteristic.

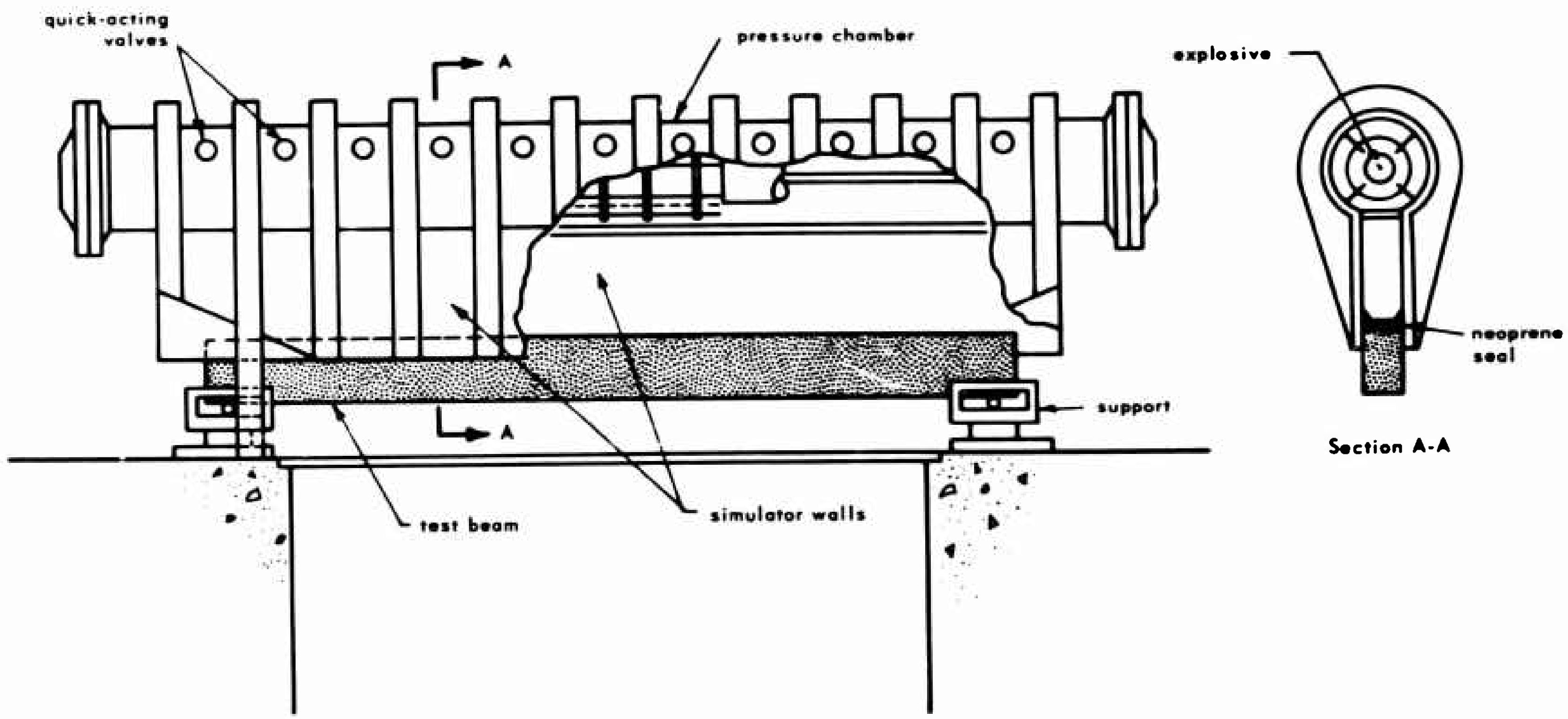


Figure 6. Schematic of beam in NCEL blast simulator.

Each beam was given an initial blast load of about 7 psi to determine the natural frequency. The simulator was then recharged with sufficient Primacord to provide the desired test overpressure, and the above firing procedure was repeated.

After the test the beam-reaction assembly was rolled out of the simulator, and the beam was inspected. Cracks in the wood were traced with felt pens for easier identification on photographs. The beams were then photographed, and sections were cut for moisture-content determination and penetration of the chemicals.

Results and Discussion

Static Tests. The results of the static tests are given in Table 1 and Figure 7. Static strain-deflection curves are shown in Figures A-1 through A-4 in Appendix A. All beams failed in flexure; there was no horizontal shear cracking at the supports. Failure in the untreated beams was primarily due to tension failure perpendicular to the grain; the bottom laminations of the treated beams failed in simple tension. Both treated and untreated beams did not have substantial permanent deflection after the static load was removed, indicating that extensive yielding had not occurred before failure.

The presence of knots in the tension side of the beams near midspan generally controlled the location of the failure zone. The failure zone for beam U4 was through a pattern of knots approximately 16 inches from midspan on one side, although some cross-grain splitting had already occurred on the other side. Beam U3 was relatively free of surface knots and as a result had a greater load capacity. Knot patterns in the treated wood, while not as numerous or concentrated as in beam U4, still precipitated failure.

In examining the data in Table 1 and Figure 7, it should be kept in mind that there is a considerable difference in moisture content between the treated and untreated beams. Average moisture content in the treated beams was near or above the fiber-saturation point for Douglas fir; the rate of moisture loss was nearly zero in beam T6 at the date of testing.

The saturation point of wood fibers is that state in which the cell walls are saturated throughout, but the cavities of the fibers are entirely free from moisture.[8] It is presumed that at the fiber-saturation point the shrinkage of a drying wood fiber begins, and its strength properties begin to be affected. In large pieces of lumber, an abrupt change in strength properties when the average moisture content reached the fiber-saturation point would be unlikely because of nonuniformity in moisture distribution. Nevertheless, the fiber-saturation point does mark the point where strength properties of wood are in a transition stage.

Beam T1 tested at 39.8% moisture and T6 at 24.0% moisture had nearly identical load-deflection behavior, attesting to the fact that the strength of wood does not vary significantly if the moisture content is greater than the fiber-saturation point. When beam T6 was tested, the drying rate was nearly zero, indicating that the

equilibrium moisture content for the beams was near 24% under desorbing moisture conditions. Under absorbing conditions, i.e., when the treated lumber has been kiln dried and the moisture content rises to equilibrium, the equilibrium point will be somewhat lower than this value.

Investigations frequently attempt to adjust strength values of timber to a common moisture content by using published correction factors. But for wood treated with fire retardants, the problem is complicated by the presence of chemicals which tend to make the wood more hygroscopic and to increase the moisture content. Unpublished data indicate that when untreated Douglas fir has a moisture content of 14%, fire-retardant-treated wood may have a moisture content of from 15 to 30%, depending upon the chemicals used and their retention.[1] No corrections for moisture content were applied to strength values in this investigation, because the moisture content that the treated beams attained under the conditions of storage was assumed to be a unique characteristic of the material. On the basis that high moisture content and fire-retardant chemicals go hand-in-hand, no corrections were applied to the values shown in Table 1. Energy absorbed, a measure of toughness, was determined from the area under the load-deflection curves for the beams. Up to the point of major cracking, deflections were assumed elastic and resulted from continuous curvature changes along the beam axis; deflections beyond major cracking were attributed to concentrated rotation at midspan. Average values of stress and energy absorbed at the proportional limit and ultimate loads were 25 to 35% lower in the treated beams than in the untreated control beams.

The modulus of elasticity was calculated from the load-deflection curves and, therefore, includes the effects of shear deflections. Shear deflections were determined from the elastic-strain-energy method and measured flexural strains. The method is shown in Appendix B. When shear deflections are considered, a better approximation of the true modulus of elasticity in bending is 2.08×10^6 psi for the untreated beams and 1.92×10^6 psi for the treated beams. Shear deflections in the elastic range were calculated as 10 to 20% of the total deflection.

Dynamic Tests. Nine beams were subjected to dynamic loading. Beams U3 and U5 received two cycles of loading to establish the response curve in the elastic range. Beam U5 failed on the second cycle of loading, but beam U3 was undamaged after the second cycle and was later loaded statically to failure.

The response of the beams to the imposed loads was generally quite typical of beam response to blast loading. The results are summarized in Tables 2 and 3. Typical time variation of the measured quantities is shown in Figures C-1 through C-6 in Appendix C.

The load-time curves closely approximate a step-pulse loading of long duration. In all cases the peak load was reached in about 3 to 4 milliseconds. Some disturbance is present in the initial portion of the load curve; however, the frequency of these perturbations is much higher than the natural frequency of the beam, and the influence is insignificant. The load function can be adequately represented by an average pressure-time curve drawn through the perturbations.

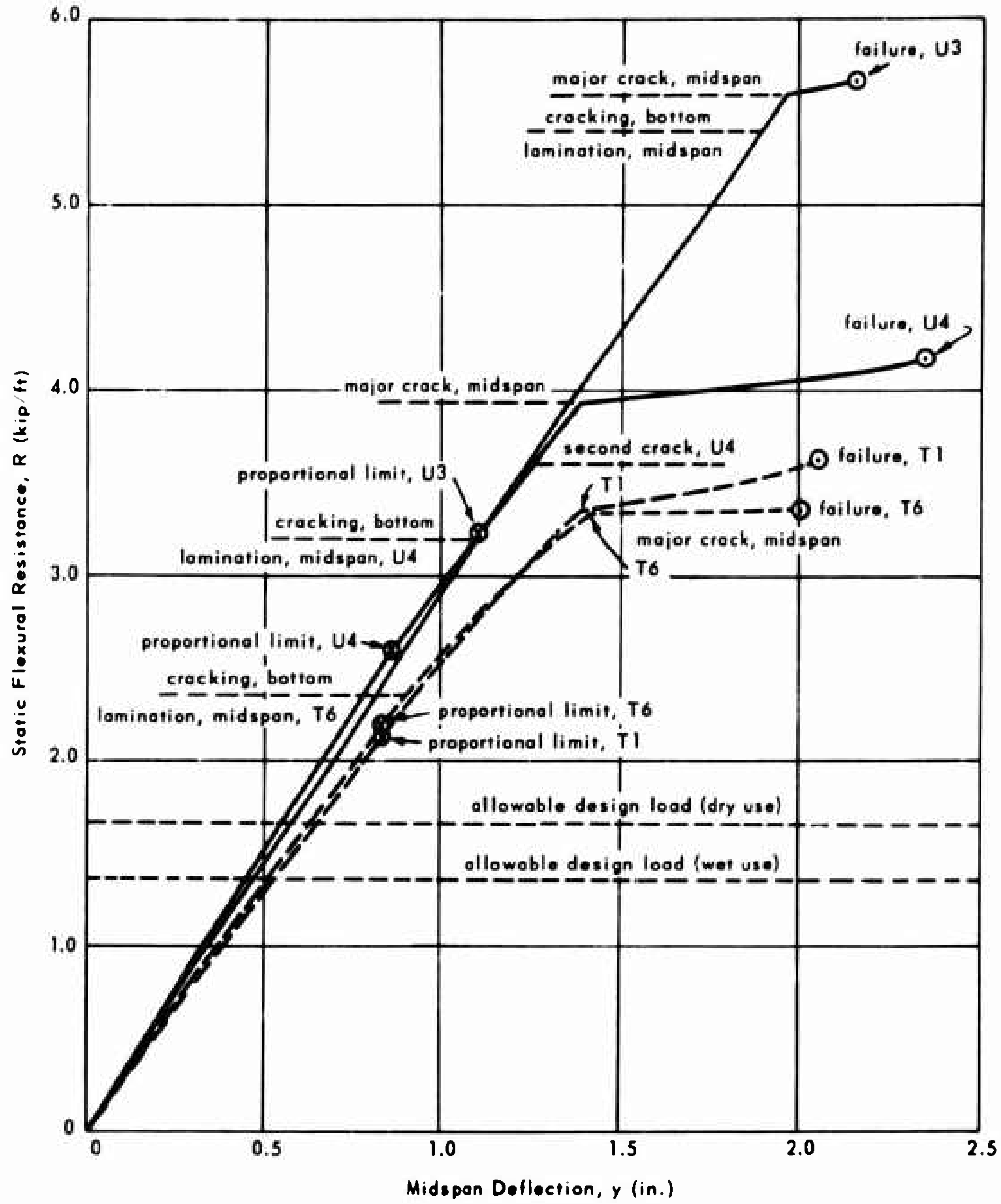


Figure 7. Measured static flexural resistance diagrams.

Table 1. Static Beam Tests

Beam[1]	Moisture Content (% of dry wood)	Modulus of Elasticity (10^6 psi)	Proportional Limit: Load (kip ft)	Proportional Limit: Deflection ℄ (in.)	Proportional Limit: Maximum Fiber Stress (psi)	Proportional Limit: Energy Absorbed (in.-lb / cu in.)	Ultimate Load: Load (kip ft)	Ultimate Load: Deflection ℄ (in.)	Ultimate Load: Modulus of Rupture (psi)	Ultimate Load: Energy Absorbed (in.-lb / cu in.)	Ultimate Load: Maximum Shear Stress at Support (psi)
U3	5.0	1.75	3.25	1.11	4,300	0.94	5.62	2.15	7,450	2.73	576
U4	4.4	1.83	2.60	0.86	3,440	0.55	4.25	2.35	5,630	3.06	436
T1	39.8	1.54	2.14	0.82	2,840	0.46	3.54	2.05	4,690	2.15	364
T6	24.0	1.61	2.20	0.83	2,920	0.48	3.40	2.00	4,505	2.04	349

1/ U designates untreated beams, T designates treated beams.

Table 2. Dynamic Beam Tests

Beam[1]	Applied Load (kip ft)	Proportional Limit: Resistance (kip/ft)	Proportional Limit: Deflection ℄ (in.)	Proportional Limit: Maximum Fiber Stress (psi)	Proportional Limit: Energy Absorbed (in.-lb / cu in.)	Ultimate Load: Resistance (kip/ft)	Ultimate Load: Deflection ℄ (in.)	Ultimate Load: Modulus of Rupture (psi)	Ultimate Load: Energy Absorbed (in.-lb / cu in.)	Time to Failure (sec)	Elastic Strain Rate (in./in./sec)
Natural Period of Vibration = 0.025 sec											
U1	3.72	2.90	0.85	3,840	0.65	3.80	2.00	5,040	2.50	0.0093	0.57
U2	3.88	3.55	1.20	4,700	1.12	4.27	2.00	5,670	2.60	0.0085	0.54
U3(1)[2]	2.84	-	-	-	-	-	-	-	-	-	0.41
U3(2)	3.32	3.60	1.20	4,770	1.13	-	-	-	-	-	0.50
U5(1)	3.79	-	-	-	-	-	-	-	-	-	0.46
U5(2)	3.93	3.70	0.99	4,900	0.97	6.72	2.35	8,900	4.45	0.0129	0.49
U6	3.65	4.15	1.38	5,500	1.44	4.76	2.37	6,315	3.44	0.0124	0.53
Natural Period of Vibration = 0.026 sec											
T2	3.74	3.46	1.17	4,580	1.06	4.11	1.95	5,450	2.34	0.0085	0.38
T3	3.84	2.11	0.81	2,800	0.45	3.29	1.85	4,360	1.82	0.0100	0.39
T4	3.98	3.27	1.12	4,340	0.95	3.85	1.85	5,100	2.07	0.0096	0.41
T5	4.03	2.68	1.00	3,560	0.70	3.29	1.75	4,360	1.68	0.0091	0.49

1/ U designates untreated beams, T designates treated beams.
2/ Number in parentheses indicates first or second loading of beam.

Table 3. Effects of Strain Rate and Treatment

Beam 1/	Proportional Limit		Ultimate Load		Modulus of Elasticity (10^6 psi)	Moisture Content (% of oven-dry wood)	Salt Content (% of oven-dry wood)
	Stress (psi)	Energy Absorbed (in.-lb / cu in.)	Stress (psi)	Energy Absorbed (in.-lb / cu in.)			
Static Tests							
U3	4,300	0.94	7,450	2.73	1.75	4.4	-
U4	3,440	0.55	5,630	3.06	1.82	4.4	-
Average	3,870	0.74	6,540	2.90	1.79		
T1	2,840	0.46	4,690	2.15	1.54	39.8	28.7
T6	2,920	0.48	4,505	2.04	1.61	24.0	17.0
Average	2,880	0.47	4,597	2.10	1.57		
Dynamic Tests							
U1	3,840	0.65	5,040	2.50	2.04	4.7	-
U2	4,700	1.12	5,670	2.60	1.75	3.3	-
U3	4,700	1.13	-	-	1.75	4.4	-
U5	4,900	0.97	8,900	4.45	2.23	7.6	-
U6	5,500	1.44	6,315	3.44	1.77	9.3	-
Average	4,728	1.06	6,481	3.25	1.91		
T2	4,580	1.06	5,450	2.37	1.76	40.1	17.3
T3	2,800	0.45	4,360	1.82	1.54	45.9	20.2
T4	4,340	0.95	5,100	2.07	1.75	45.9	18.1
T5	3,560	0.70	4,360	1.68	1.60	36.5	27.2
Average	3,820	0.79	4,817	1.98	1.66		
Strain Rate Effect (dynamic avg/static avg)							
U	1.22	1.42	0.99	1.12	1.07		
T	1.33	1.68	1.05	0.94	1.06		
Treatment Effect (treated avg/untreated avg)							
Static	0.74	0.63	0.70	0.72	0.88		
Dynamic 2/	0.81	0.74	0.74	0.61	0.87		

1/ U designates untreated beams; T designates treated beams.
2/ Includes strain rate effect.

The strain and deflection curves for beam U3(1) shown in Figures C-1 and C-2 indicate that the period of oscillations is about 25 milliseconds. The regularity in these curves indicates that the higher modes of vibration do not appreciably influence the behavior of these uniform, symmetrically loaded beams and that the spring-mass analogy[9] can be used to analyze the results with reasonable accuracy.

Strain-gage data from the interior gages on the beams were of questionable value due to an error in instrumentation. The amplifiers were overloaded at a relatively low level of strain, and the output from the gages either oscillated at the band edge or dropped to the center frequency of the amplifier. Strain gages on the top and bottom laminations performed satisfactorily.

Dynamic resistance was determined from the acceleration records after graphically averaging the oscillations corresponding to the third mode of elastic vibration. The resistance curves shown in Figure 8 were determined from a force equilibrium using Newton's second law and a single-degree-of-freedom analysis. In this equivalent system, the load on the spring is the total load on the beam, and the mass of the system is taken as 0.769 times the actual mass of the beam. The mechanical properties at proportional limit and ultimate resistance can then be determined from the resistance - deflection curves.

Under dynamic loading the proportional limit stress was about 2.1 times the static allowable design stress, as determined from the dynamic resistance curves. The average measured dynamic magnification factor was about 1.9; i.e., the maximum elastic deflection resulting from a given dynamic load was about 1.9 times the static deflection for the same load. Thus, the proportional limit was reached at a dynamic load of 2.1 divided by 1.9, or about 1.1 times the static design load. This is important in utilizing the reserve strength of wood in designing to resist dynamic loads.

The dynamic ultimate resistance in the untreated beams was about 1.6 times the static design load for dry lumber; in the treated beams the dynamic ultimate resistance was about 1.4 times the static design load for wet lumber. This usable strength, however, should probably be left in reserve due to the variations in strength properties of lumber and the lack of ductility at ultimate deflection.

Strain-rate effect and effect of treatment are summarized in Table 3. The effect of dynamic loading on the modulus of elasticity was insignificant in these tests. The stress at the proportional limit was increased 22% and 33%, respectively, in the untreated and treated beams as determined from the dynamic resistance curves; the corresponding energy absorbed to the proportional limit increased 42% and 68%. Dynamic loading had little effect on the ultimate strength of either treated or untreated beams. These results indicate that higher proportional limit stresses can be realized under rapid strains, but that any increase in ultimate strength is probably offset by knots and other imperfections in structural-size lumber. These results differ from results of other investigations which report substantial increases in ultimate strength of specimens subjected to dynamic loading.[10, 11, 12, 13] However, test results from small specimens which are free of natural imperfections are not necessarily typical of the behavior of average structural-size members.

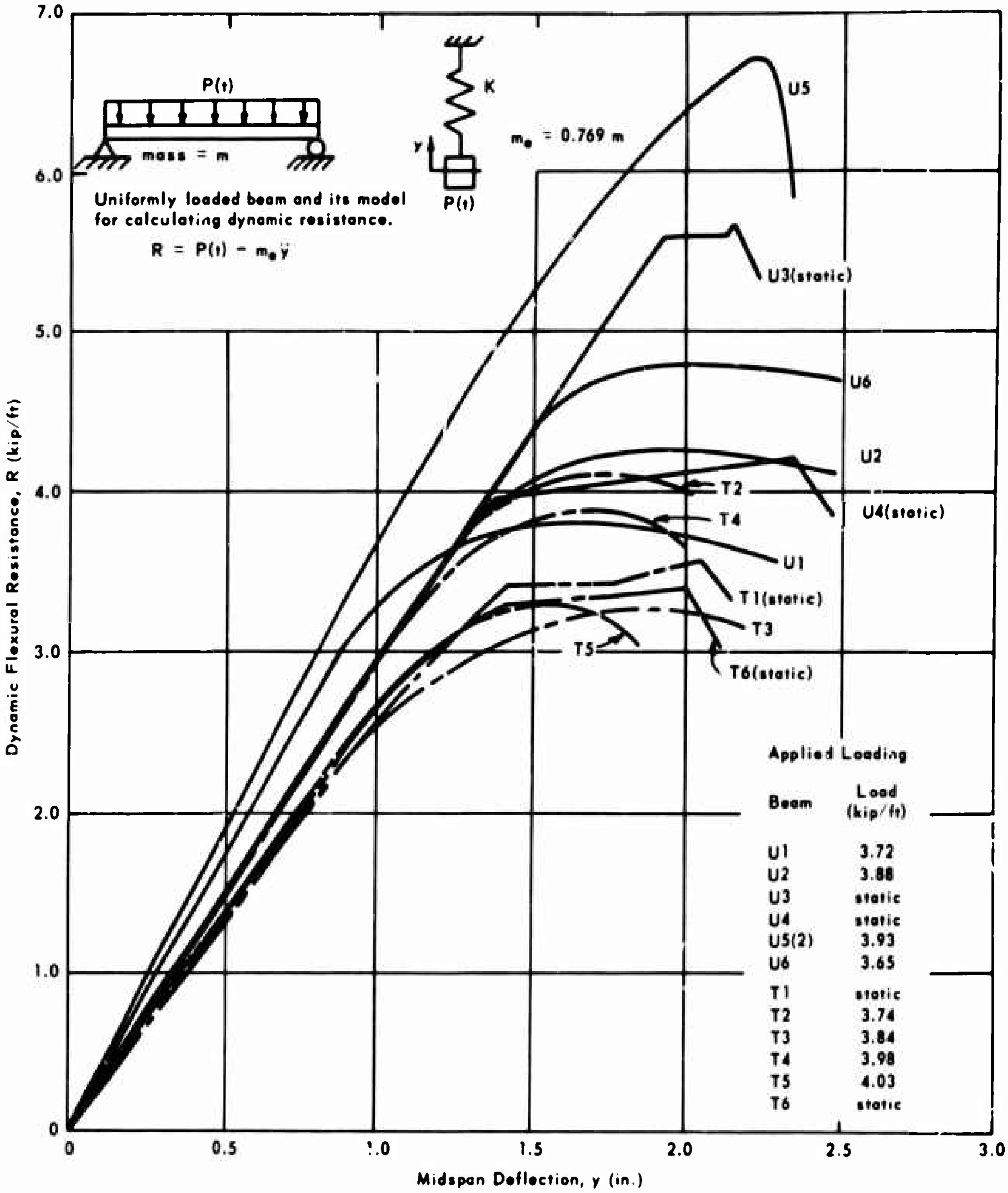


Figure 8. Dynamic flexural resistance diagrams.

Average mechanical properties of treated wood at proportional limit and ultimate deflection were 20 to 40% less than in the untreated control beams, as shown in Table 3. The modulus of elasticity was reduced by about 12%.

PLYWOOD SHEETS

The second phase of the investigation was to study the effect of the fire-retardant treatment on the strength of plywood sheets. It was desired to compare the strength of treated and untreated plywood sheets used for shear resistance in walls and diaphragm panels. This phase was concerned with the shear strength through the thickness of the plywood panels subjected to static and dynamic loading.

Description of Sheets

To obtain treated and control panels which were matched, three test panels 8 feet long, 4 feet wide, and 1/2 inch thick, of 5-ply, A-B Exterior Douglas fir were selected, and each panel was cut into two sections, 4x4 feet. Of the original sheets, designated as A, B, and C, the half panels to receive treatment were labeled AT, BT, and CT. These half panels were given the same fire-retardancy treatment used for the laminated beams. The sheets were then cut into test-size specimens and air-dried to equilibrium moisture content before testing.

The test specimen is shown schematically in Figure 9. These specimens were prepared by gluing plywood rails, 1 inch thick by 2 inches wide to the panels. The shearing area between the rails was 8-3/4 inches square. Average thickness of all untreated specimens was 0.512 inch; average thickness of treated specimens was 0.528 inch in panels A and C and 0.531 inch in panel B.

Test Equipment

The plywood sheets were loaded in shear by means of the frame shown in Figure 10. The frame, pinned at the four corners, was fastened to the test specimen by 1/2-inch bolts that passed through 1/2-inch-thick aluminum side plates. Aluminum was used in the side plates to minimize inertial forces in the dynamic tests. At the corners, case-hardened mild steel bearing blocks, pivoting on a 1-inch-diameter drill rod provided the pinned-end condition. The bearing blocks were connected to the side plates with 1/4-inch-diameter roll-pins. Match marks were punched on each piece to ensure that assembly would be the same for each test. Assembly was simple, requiring approximately 20 minutes to remove a loaded specimen and install a new one.

A concentrated load applied on the vertical diagonal is transmitted as an axial force in the side plates through the pinned connections at the corners, which in turn applies a shearing load to the edges of the plywood. Buckling of the plywood along the compression diagonal was not critical.

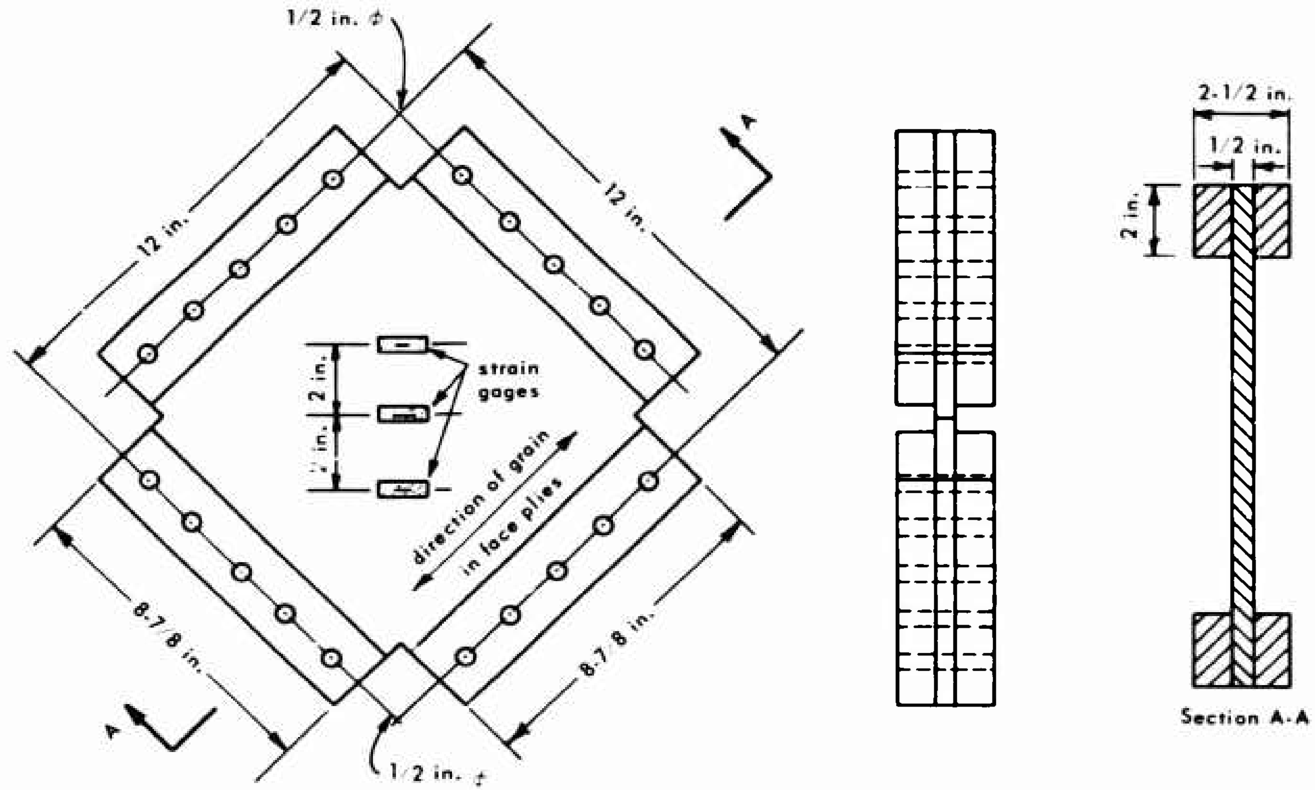


Figure 9. Shear through the thickness specimen.

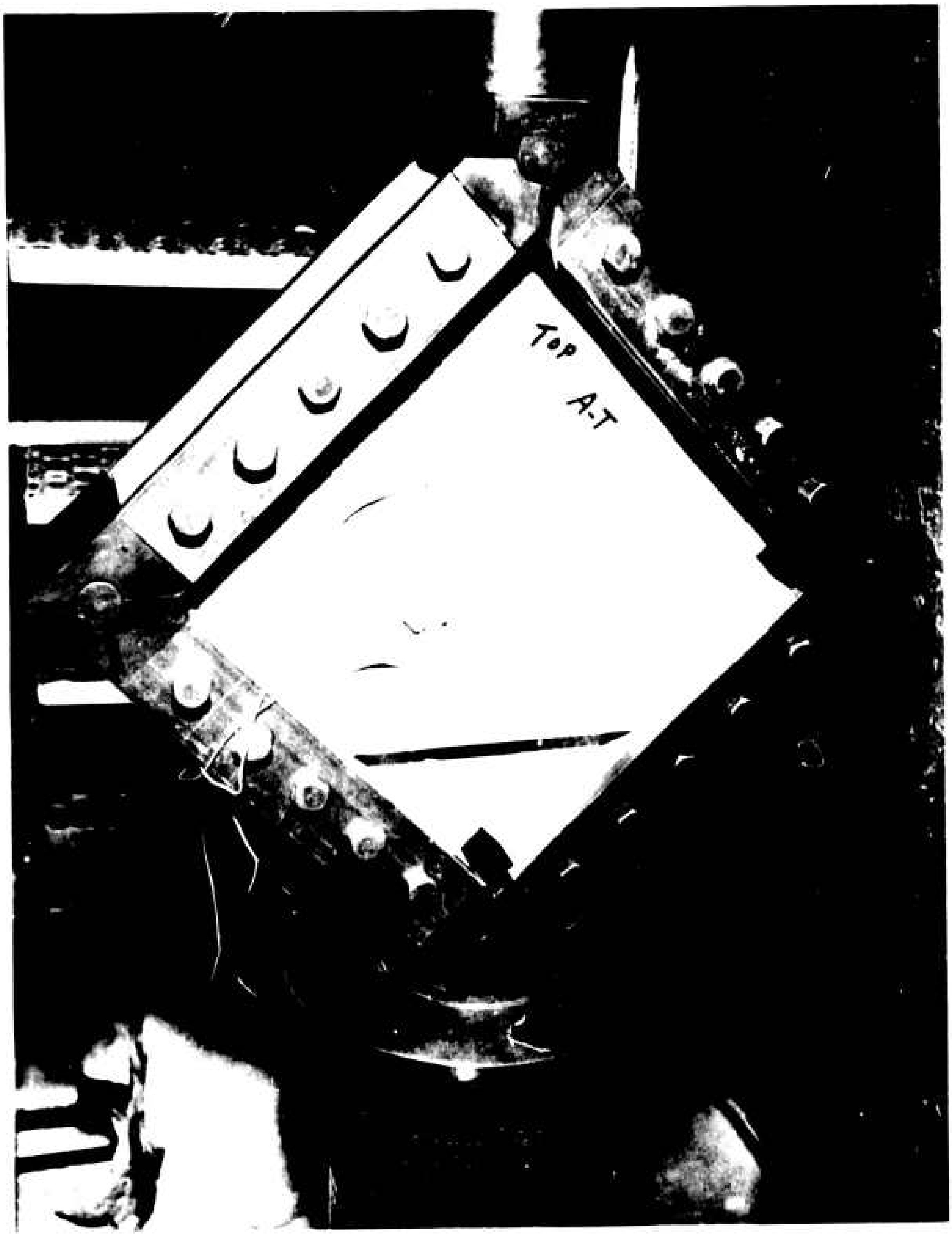


Figure 10. Shear loading frame.

Static tests were conducted in a 20,000-pound-capacity Riehle testing machine using a head speed of 0.06 inch per minute which was the minimum rate for this machine. Dynamic tests were conducted with the NCEL 50,000-pound dynamic materials testing machine[14] shown in Figure 11.

Instrumentation

Strain measurements were taken on the compression diagonal, the vertical reaction, and the displacement of the loading head of the testing machine. Strain gages were placed perpendicular to the compression diagonal and at an angle of 45 degrees with the grain of the face plies (Figure 9). At each location shown, a pair of type A5-1, SR-4 electric strain gages were bonded to opposite faces of the sheet and wired to opposite arms of a Wheatstone bridge. Dummy gages bonded to Douglas fir plywood sheets of the same thickness were used to complete the bridge.

Displacement of the loading head was measured with a Bourns potentiometer. The load applied to the test specimen was read from the dial on the Riehle testing machine for the static tests and was measured with a load cell supporting the frame in the dynamic tests.

Test data from the static tests were recorded on a Budd model A-110 digital strain indicator; data from the dynamic tests were recorded on an oscillograph using Consolidated Electrodynamics Corporation System D, 3-kc amplifiers.

Test Procedure

Preparation of the sheets for testing was the same for both static and dynamic tests. A template was placed over the sheets as a guide for drilling the bolt holes through the plywood rails and test specimen. Holes were drilled, and the shear loading frame was bolted to the specimen in such a manner that assembly match marks on the frame coincided. The pins were inserted at the corners, and the frame was aligned until the pins were seated properly and rotated freely. Then the bolts were tightened, and the entire fixture was placed in the testing machine. All electrical connections were made, and the specimen was ready for testing.

After testing, the frame was disassembled, and a section was cut from the test specimen for determination of moisture content and salt retention. Specimens approximately 8-3/4 inches square were oven-dried at 217°F for a period of 48 hours. The moisture content and the original and final weights of the matching test specimens were used to calculate salt-retention values in terms of dry salt as a percentage of the oven-dry weight of wood substance.

The assumptions made in the salt-retention calculations were that the moisture content of matching half-panels was the same immediately after the original cutting (before the panels were treated), and that the moisture in all half-panels was uniformly distributed at the time each was cut into test specimens. The equations used to calculate moisture-content and salt-retention values are given in Appendix D.

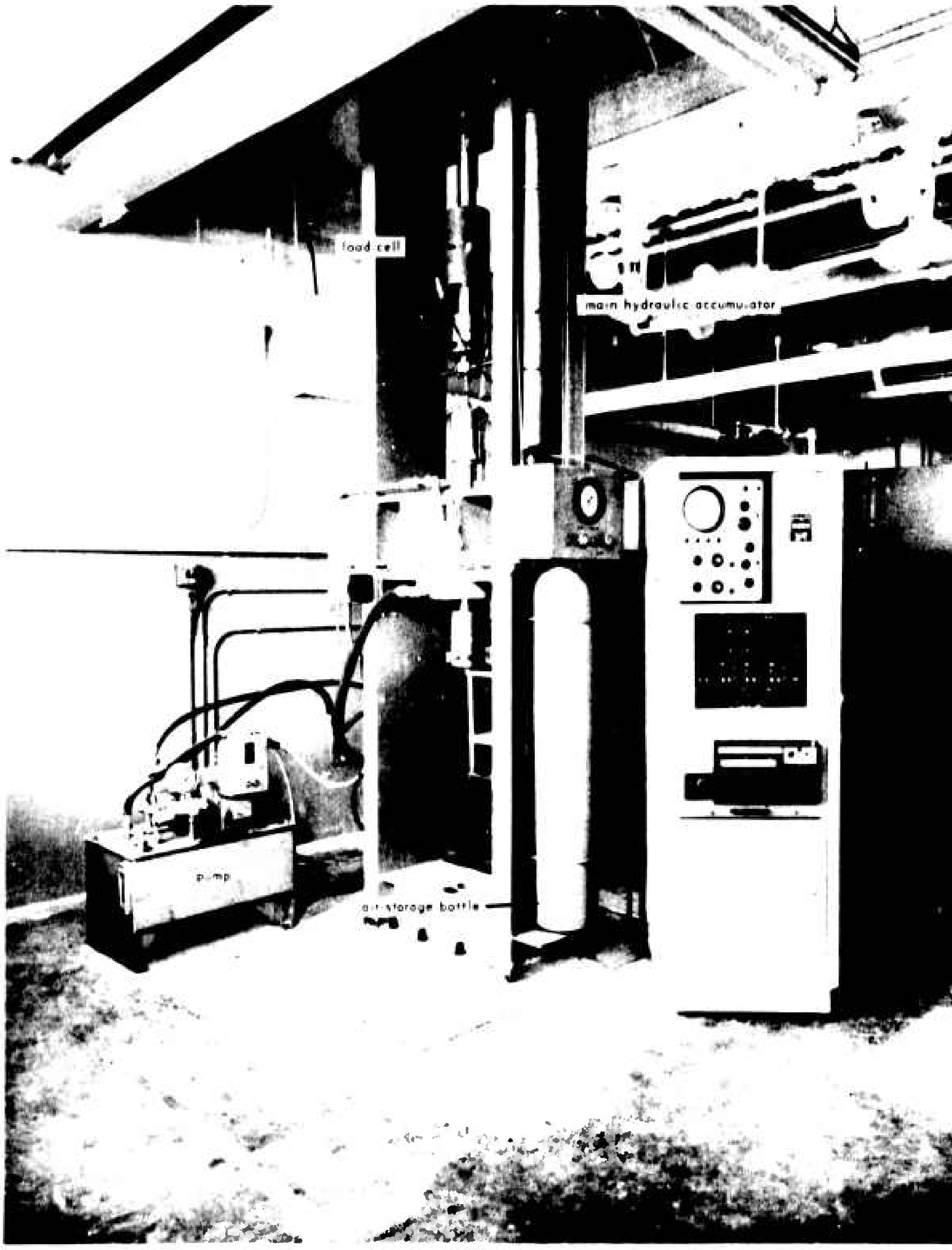


Figure 11. NCEL dynamic testing machine.

Static Tests. Static tests were conducted on one treated and one untreated panel from each of sheets B and C to study the static load-deformation properties of the plywood and also to observe the behavior of the loading frame. Loading was continuous to failure at a head velocity of about 0.06 inch per minute, with readings being taken at 100-pound increments up to the point where the load could not be maintained.

Dynamic Tests. Two treated and two untreated specimens from each of the original sheets were tested under dynamic loads. The average rate of loading for these tests was about 31 in./sec, resulting in a shear strain rate of about 5.0 rad/sec.

Figure 10 shows a test specimen in the NCEL dynamic materials testing machine. The frame is resting on the load cell which measures the resistance of the specimen. To load the specimen, the machine is first brought up to a predetermined operating pressure. A switch is then closed to start an electronic time relay which activates a series of solenoid valves that control the loading. The head velocity of the machine, and hence the strain rate in the specimen, is controlled by several hand-operated valves; the settings for these valves are established before each test and are not changed until a new head velocity is desired. The recording oscillograph is controlled manually; it is started just before firing the machine and turned off a short time after firing.

Results and Discussion

Static Tests. In all cases, specimens failed in a plane perpendicular to the panels and perpendicular to the direction of the grain in the face plies. Although the specimens distorted and splintered badly, the rails did not shear off completely. Figure 12 shows the condition of the specimens before and after a test.

Results of the static tests are given in Figure 13 and Tables 4 and 5. Because only one treated and one untreated specimen were taken from panels B and C, the results are not conclusive, but indicate that treatment reduces the mechanical properties of plywood in shear. In panel B the treatment reduced modulus of rigidity and maximum shear stress by 22 and 36%, respectively. In panel C the reductions were 31 and 24%. Shear strains at maximum load were reduced 16% by treatment in panel B but were increased 7% in panel C.

In terms of load-carrying capacity (maximum load per inch of length) and shear stiffness (modulus of rigidity times thickness), the reductions resulting from treatment were 34 and 19%, respectively, in panel B and 22 and 29%, respectively, in panel C.

A comparison of these results with results of other investigators[4] shows some similarities in trends. The average reduction in modulus of rigidity and maximum shear stress was 12 and 13%, respectively, from one treatment process and 17 and 25%, respectively, from another. (Treatments were designated as A and B respectively.) Load-carrying capacity and shear stiffness were reduced by 11 and 9% respectively, in treatment A and 23 and 14%, respectively, in treatment B.

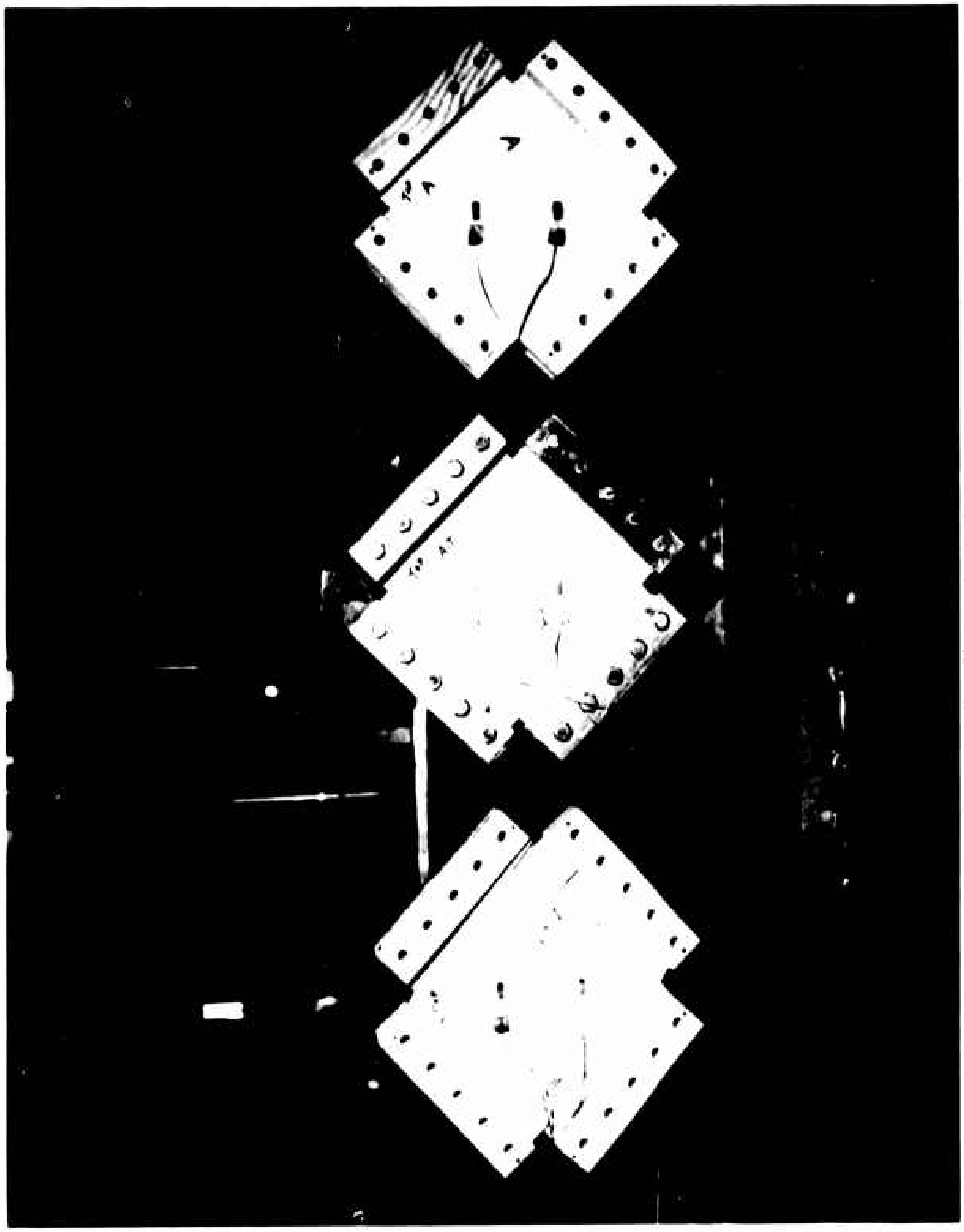


Figure 12. Plywood specimens.

Table 4. Summary of Test Results, Plywood Shear-Through-the-Thickne

Specimen	Panel	Thickness Ratio[1]	Salt Content (%)	Moisture Content[2]		Modulus of Rigidity			Maximum Load	
				Treated (%)	Control (%)	Treated (psi)	Control (psi)	Ratio[3]	Treated (lb in.)	Cont (lb i
Static Tests										
BT	B	1.037	16.5	12.1	7.0	95,100	121,400	0.784	429	64
CT	C	1.031	10.6	11.1	8.0	92,800	134,300	0.691	470	59
Dynamic Tests										
AT-1	A	1.031	19.2	10.2	7.8	60,000	92,900	0.646	630	66
AT-2	A	1.031	19.2	10.1	7.7	60,000	76,100	0.789	670	81
Avg	A	1.031	19.2	10.2	7.8	60,000	84,500	0.717	650	73
BT-1	B	1.037	16.5	10.5	7.3	43,500	52,600	0.827	615	69
BT-2	B	1.037	16.5	9.2	7.1	66,200	78,900	0.839	704	74
Avg	B	1.037	16.5	9.8	7.2	54,850	65,750	0.833	655	72
CT-1	C	1.031	10.6	8.8	5.9	57,800	59,600	0.970	825	81
CT-2	C	1.031	10.6	8.8	5.2	63,800	57,400	1.111	720	68
Avg	C	1.031	10.6	8.8	5.5	60,800	58,500	1.041	772	74

1/ Thickness of treated specimens divided by that of control.
2/ Dried at 217°F for 48 hours.
3/ Treated values divided by control values.

A

4. Summary of Test Results, Plywood Shear-Through-the-Thickness

isture Content2/		Modulus of Rigidity			Maximum Load/in. of Length			Maximum Shear Stress		
ated (%)	Control (%)	Treated (psi)	Control (psi)	Ratio3/	Treated (lb/in.)	Control (lb/in.)	Ratio3/	Treated (psi)	Control (psi)	Ratio3/
Static Tests										
2.1	7.0	95,100	121,400	0.784	429	646	0.664	808	1,262	0.640
1.1	8.0	92,800	134,300	0.691	470	599	0.785	890	1,170	0.760
Dynamic Tests										
0.2	7.8	60,000	92,900	0.646	630	664	0.949	1,193	1,297	0.920
0.1	7.7	60,000	76,100	0.789	670	810	0.827	1,269	1,605	0.791
0.2	7.8	60,000	84,500	0.717	650	737	0.888	1,231	1,451	0.856
0.5	7.3	43,500	52,600	0.827	615	695	0.885	1,158	1,357	0.853
9.2	7.1	66,200	78,900	0.839	704	744	0.946	1,326	1,453	0.913
9.8	7.2	54,850	65,750	0.833	655	720	0.916	1,242	1,405	0.883
8.8	5.9	57,800	59,600	0.970	825	810	1.019	1,562	1,582	0.987
8.8	5.2	63,800	57,400	1.111	720	687	1.048	1,364	1,342	1.016
8.8	5.5	60,800	58,500	1.041	772	748	1.034	1,463	1,462	1.002

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Table 5. Summary of Test Results, Plywood Shea

Specimen	Panel	Thickness Ratio[1]	Salt Content (%)	Maximum Shear Strain			
				Treated (μ rad)	Control (μ rad)	Ratio[2]	Treate (lb/in
Static Tests							
BT	B	1.037	16.5	15,200	18,000	0.844	50,5
CT	C	1.031	10.6	19,200	18,000	1.067	48,9
Dynamic Tests							
AT-1	A	1.031	19.2	22,000	21,200	1.038	31,7
AT-2	A	1.031	19.2	32,000	35,200	0.909	31,7
Avg	A	1.031	19.2	24,000	28,200	0.973	48,2
BT-1	B	1.037	16.5	33,600	36,000	0.933	23,1
BT-2	B	1.037	16.5	25,600	24,800	1.032	35,1
Avg	B	1.037	16.5	29,600	30,600	0.983	29,1
CT-1	C	1.031	10.6	12,800	35,600	0.921	30,5
CT-2	C	1.031	10.6	28,800	34,000	0.847	33,7
Avg	C	1.031	10.6	20,800	34,800	0.884	32,1

1/ Thickness of treated specimens divided by that of control.
2/ Treated values divided by control values.

A

5. Summary of Test Results, Plywood Shear-Through-the-Thickness

nt	Maximum Shear Strain			Shear Stiffness			Energy Absorbed to Ultimate Load		
	Treated (μ rad)	Control (μ rad)	Ratio 2/	Treated (lb/in.)	Control (lb/in.)	Ratio 2/	Treated (in.-lb)	Control (in.-lb)	Ratio 2/
	Static Tests								
	15,200	18,000	0.844	50,500	62,200	0.812	-	-	-
	19,200	18,000	1.067	43,900	68,800	0.711	-	-	-
	Dynamic Tests								
	22,000	21,200	1.038	31,700	47,500	0.668	680	1,020	0.667
	32,000	35,200	0.909	31,700	39,000	0.812	820	1,190	0.689
	24,000	28,200	0.973	48,200	43,250	0.740	750	1,105	0.678
	33,600	36,000	0.933	23,100	26,900	0.859	950	1,120	0.848
	25,600	24,800	1.032	35,100	40,400	0.869	730	1,420	0.514
	29,600	30,600	0.983	29,100	33,650	0.864	840	1,270	0.681
	12,800	35,600	0.921	30,500	30,500	1.000	1,150	1,330	0.865
	28,800	34,000	0.847	33,700	29,400	1.146	1,200	1,130	1.062
	20,800	34,800	0.884	32,100	29,950	1.073	1,175	1,230	0.964

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lues.

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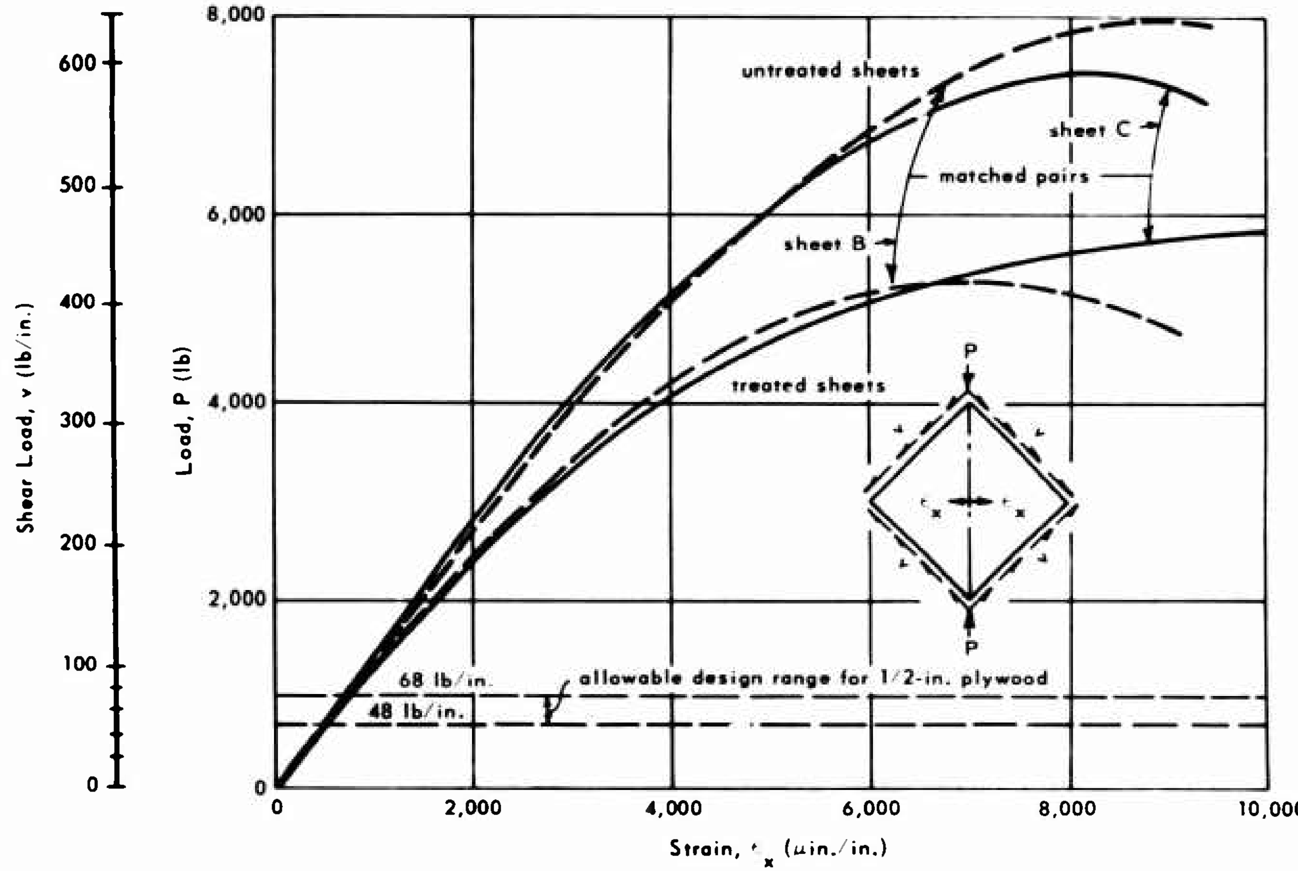


Figure 13. Static load-strain curves for plywood sheets in shear.

Dynamic Tests. The modulus of rigidity, maximum load per inch of length, shear stress and shear strain at maximum load, shear stiffness (modulus of rigidity times thickness), and energy absorbed to ultimate load of six treated specimens are compared with corresponding values from untreated matched control specimens in Tables 4 and 5. A typical oscillogram of the recorded experimental data is shown in Figure 14. In general, the effects of the treatment were not as significant in the dynamic tests as in static tests. In some treated specimens, the mechanical properties were improved over those of the untreated specimens. For example, in the specimens from panel C, some mechanical properties were improved by as much as 7% by treating. Exceptions to this in specimens from panel C were maximum shear strain and energy absorbed to ultimate load, in which average values were reduced 12 and 4%, respectively.

In the treated specimens from panel B, average values for modulus of rigidity, maximum shear stress, shear stiffness, and energy absorbed to ultimate load were lower by 17, 12, 14, and 32%, respectively, than corresponding values from the untreated specimens. Average maximum load in the treated specimens was reduced 8%; however, the shear strains at maximum load were nearly identical in treated and untreated specimens.

Treated specimens from panel A were the only specimens in which the side rails sheared off in testing. Both rails perpendicular to the direction of the face plies sheared off almost simultaneously. Average values for modulus of rigidity, maximum shear stress, shear stiffness, and energy absorbed to ultimate load were lower by 28, 14, 26, and 32%, respectively, than corresponding values from the untreated specimens. Average maximum load and maximum shear strain were reduced 11 and 3%, respectively, in the treated specimens.

The results in Tables 4 and 5 indicate that the effect of treatment on the mechanical properties of plywood is a function of the amount of salts retained in the wood. There appear to be no adverse effects when the dry salt content is approximately 10% of the weight of the dry wood, or about 3.4 lb/cu ft of plywood. The present specification covering fire-retardancy treatment of plywood requires a minimum retention of 5.0 pounds of dry salt per cubic foot of plywood.[15]

GENERAL DISCUSSION

Major Findings

These findings apply only to the type of beams, plywood panels, loading, and fire-retardant treatment investigated in this study. It is reasonable, however, to assume that the trend of these results will be similar in laminated Douglas fir beams and plywood panels of other physical dimensions subjected to fire-retardant treatments and loading other than those used in this investigation.

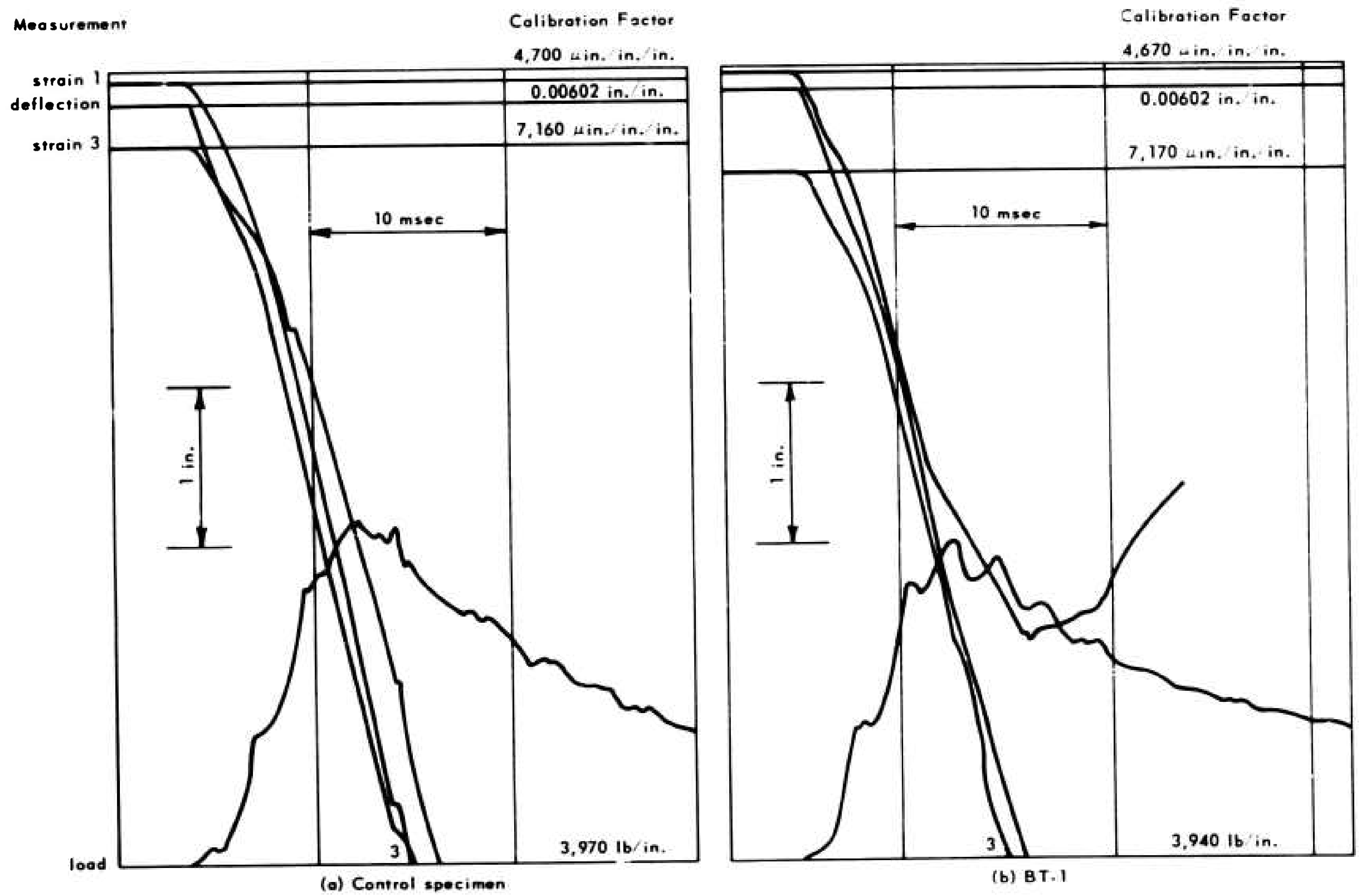


Figure 14. Oscillograms for specimen BT-1 and the control specimen.

Laminated Beams.

1. Large structural-size timbers impregnated with fire-retardant chemicals and then air-dried will retain large quantities of water over a long period of time because of the hygroscopic nature of the treated wood. Equilibrium moisture content under service environment may be quite high, approaching the fiber-saturation level for the material.

2. Normally tight surface knots may be loosened as a result of treatment, resulting in a reduction of effective cross section at those points.

3. Average values of stress and the energy absorbed at proportional limit and ultimate load were 20 to 40% lower in the treated beams than in the untreated beams. Modulus of elasticity was about 12% lower.

4. Rapid strain rates resulted in substantially increased stress and energy absorbed at the proportional limit in both treated and untreated beams; at ultimate load these increases were insignificant.

5. The proportional limit of both treated and untreated beams occurred at a dynamic load of about 1.1 times the static allowable design load. The dynamic ultimate load was between 1.4 and 1.6 times the static design load.

Plywood Sheets.

1. The hygroscopicity of plywood is increased by pressure-impregnation with fire-retardant salts, thereby resulting in a higher equilibrium moisture content than in untreated plywood.

2. The effect of treatment with fire-retardant chemicals on the mechanical properties of plywood appears to be proportional to the amount of dry salt retained in the wood. When the weight of dry salt retained was 10% of the weight of the wood, no significant adverse effects on the dynamic mechanical strength properties were observed. Higher retentions were detrimental.

3. In plywood panels containing 16.5 and 19.2% dry salt, the energy absorbed to ultimate load was reduced about 32%; corresponding average values for modulus of rigidity were reduced 17 and 28%, respectively. Maximum load was reduced 8 and 11%, respectively, at the two salt-retention levels.

Limitations of the Program

This study was undertaken to evaluate possible trends toward reduction of strength properties in wood as a result of treatment with fire-retardant formulations, and to determine the general magnitude of such reductions when dynamic and static loads are applied. The results as reported should be viewed accordingly, because the study is by no means all-inclusive. There are many variables, such as depth of penetration, method of treatment, chemicals involved, aging effects, temperature and humidity effects, etc., which must be studied before complete and precise answers can be given.

The required sample population for timber testing is necessarily large due to the large number of variables involved. Careful selection and matching of specimens is possible when small specimens are to be tested; when structural-size specimens are involved, the matching becomes more difficult, and consequently a larger sample population is required for significance in a statistical analysis.

Accuracy of Results

In experimental investigations there is always a certain degree of inaccuracy involved in recording or reducing data. The following are reasonable assumptions of the inaccuracies in the measured experimental data for these tests:

Type of Test and Measurement	Accuracy (%)
Beam Tests	
Static:	
Pressure	2-3
Deflection	2-3
Strain	4-5
Dynamic:	
Pressure	2-5
Deflection	2-5
Strain	4-5
Acceleration	2-5
Plywood Tests	
Static:	
Load	2-3
Strain	4-5
Dynamic:	
Load	4-5
Deflection	4-5
Strain	8-10

CONCLUSIONS

From the study, the following conclusions were made:

1. Equilibrium moisture content in wood that is commercially pressure-impregnated with fire-retardant chemicals which are hygroscopic will be higher than in untreated wood.

2. Bulking because of treatment with fire-retardants is in the range of 5% for laminated Douglas fir beams and plywood.

3. Reduction of strength of treated wood will be largely due to the increased moisture content.

DESIGN RECOMMENDATIONS

Stress-graded lumber provides material of designated and assured strength to meet engineering requirements. The development of stress grades and the determination of safe working stresses for them conform to well-established bases resulting from extensive research at the Forest Products Laboratory. These efforts have provided engineers with a wide range of working design values for the mechanical properties of lumber.

The results of this investigation are related to only one of the numerous stress grades of Douglas fir and one specific fire-retardancy treatment; therefore, the results must be studied and correlated with information on other chemicals and treatments before design criteria can be formulated. Until such correlations can be made, these results give some indication of the relative effect of fire-retardant treatment on the mechanical properties of wood. The following design recommendations are presented.

Laminated Beams

1. When fire-retardant lumber is used, the allowable unit stresses and modulus of elasticity should correspond to those specified for use under wet conditions.

2. Under long-duration dynamic loads, the proportional limit load can be assumed to be approximately 1.1 times the static design load.

3. Ultimate dynamic load for untreated lumber is about 1.6 times the static design load; for treated lumber the ultimate dynamic load is about 1.4 times the static design load.

Plywood in Shear

1. Modulus of rigidity and shear stiffness should be reduced approximately 20% when fire-retardant lumber is used.

2. Maximum allowable shear load in plywood should be reduced by 10% when it has been treated with fire-retardant chemicals.

3. Energy absorbed to ultimate load will be decreased by approximately 30% when plywood has been treated with fire-retardant chemicals.

As a final comment, the detrimental effects of fire-retardant treatments should not be overemphasized at the expense of the benefits that result from the use of treated wood. Not all applications call for wood in a highly stressed state. In many applications wood is used structurally at low or intermediate stress levels and under conditions where even considerable reductions in toughness can be safely tolerated.

Appendix A

STRAIN - DEFLECTION CURVES FOR STATIC BEAM TESTS

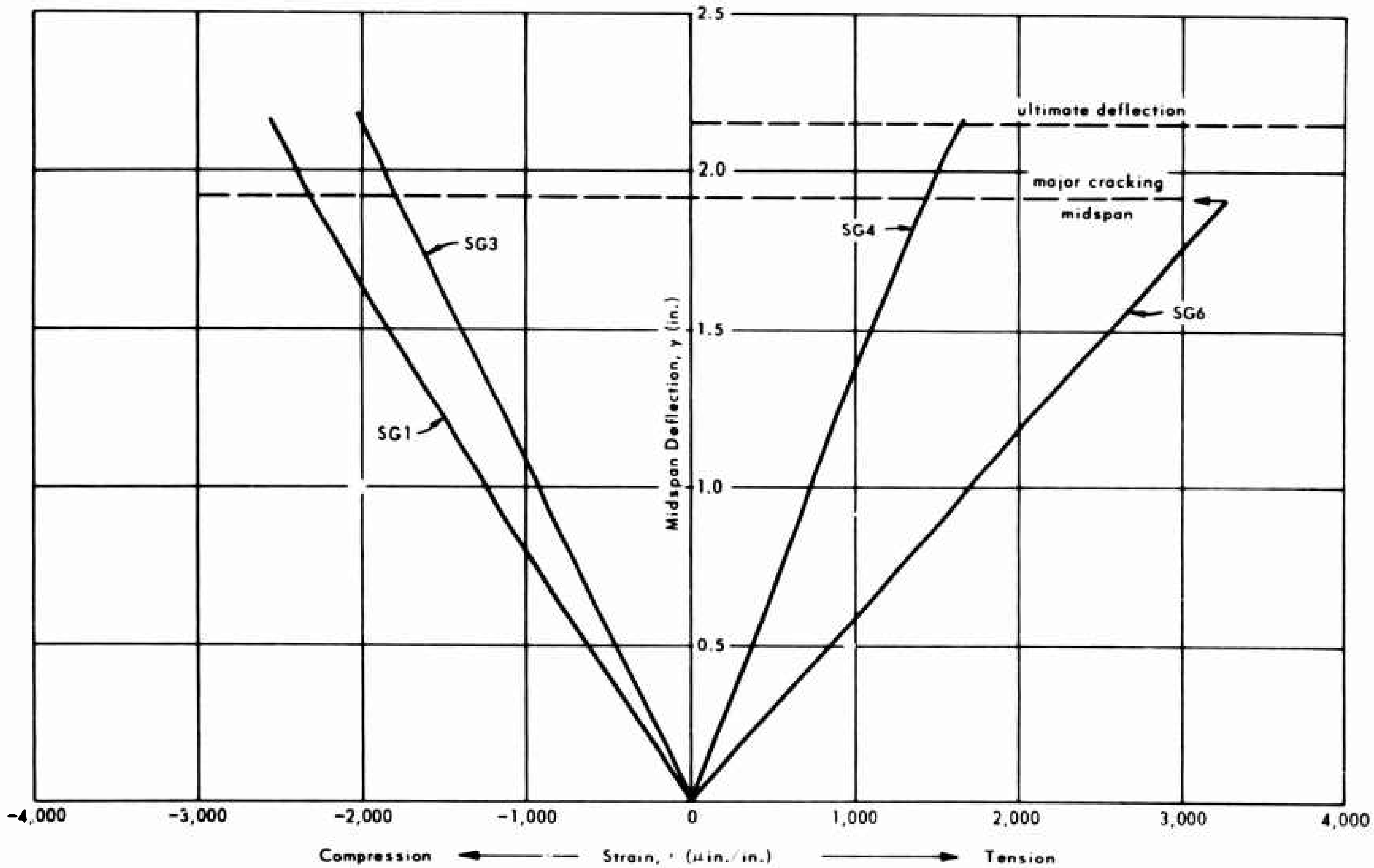


Figure A-1. Static strain-deflection curves, beam U3.

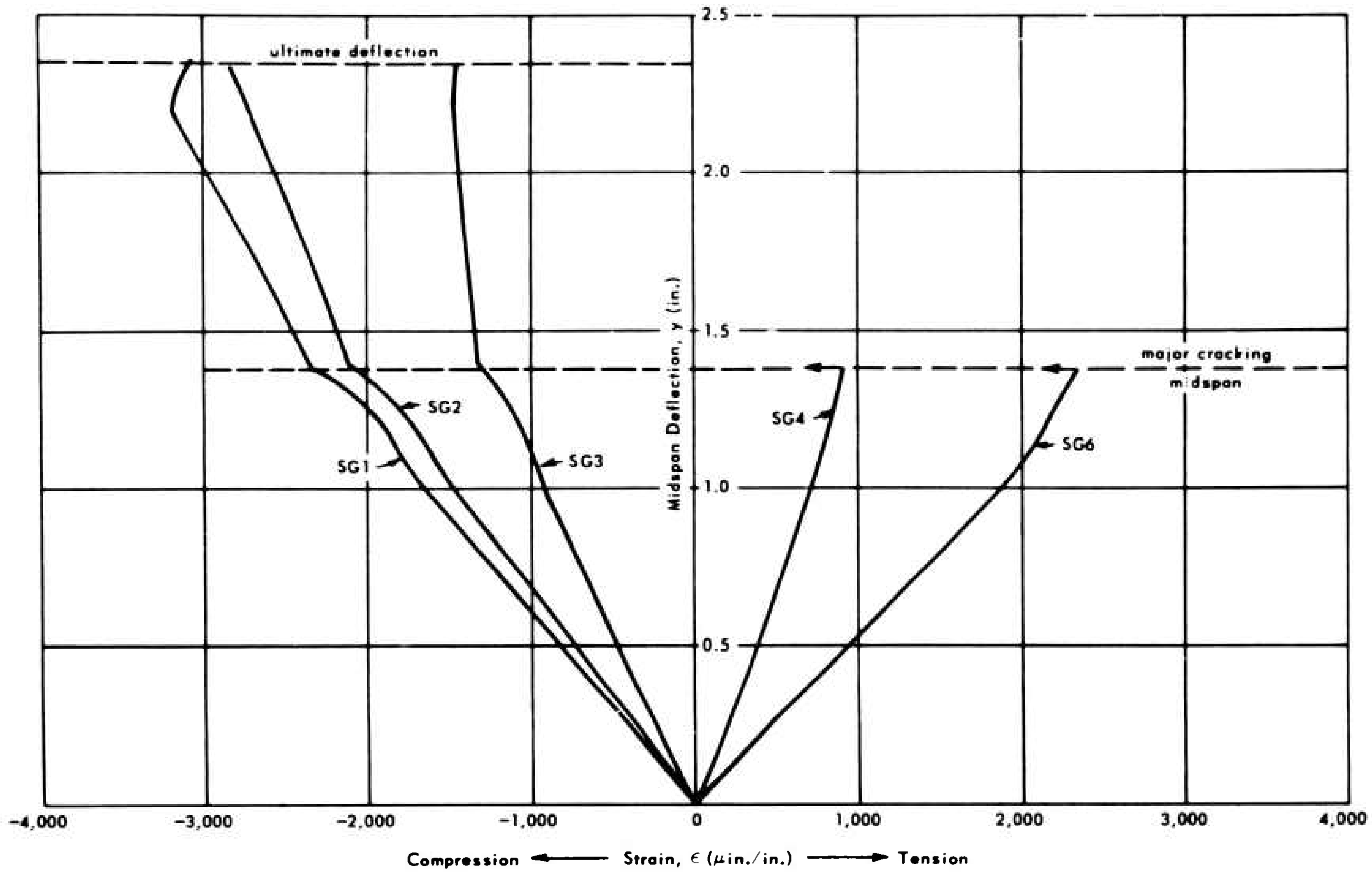


Figure A-2. Static strain-deflection curves, beam U4.

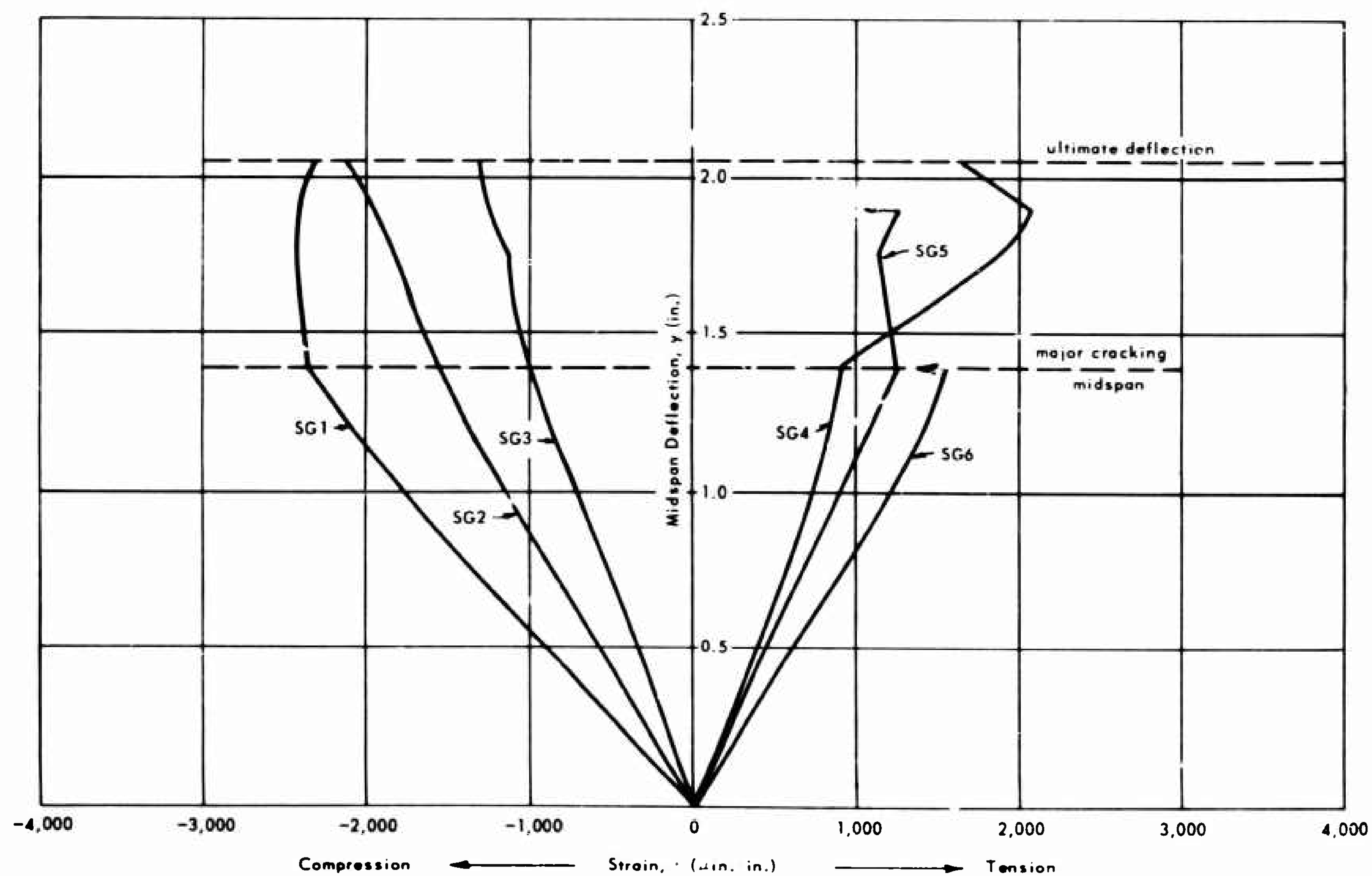


Figure A-3. Static strain-deflection curves, beam T1.

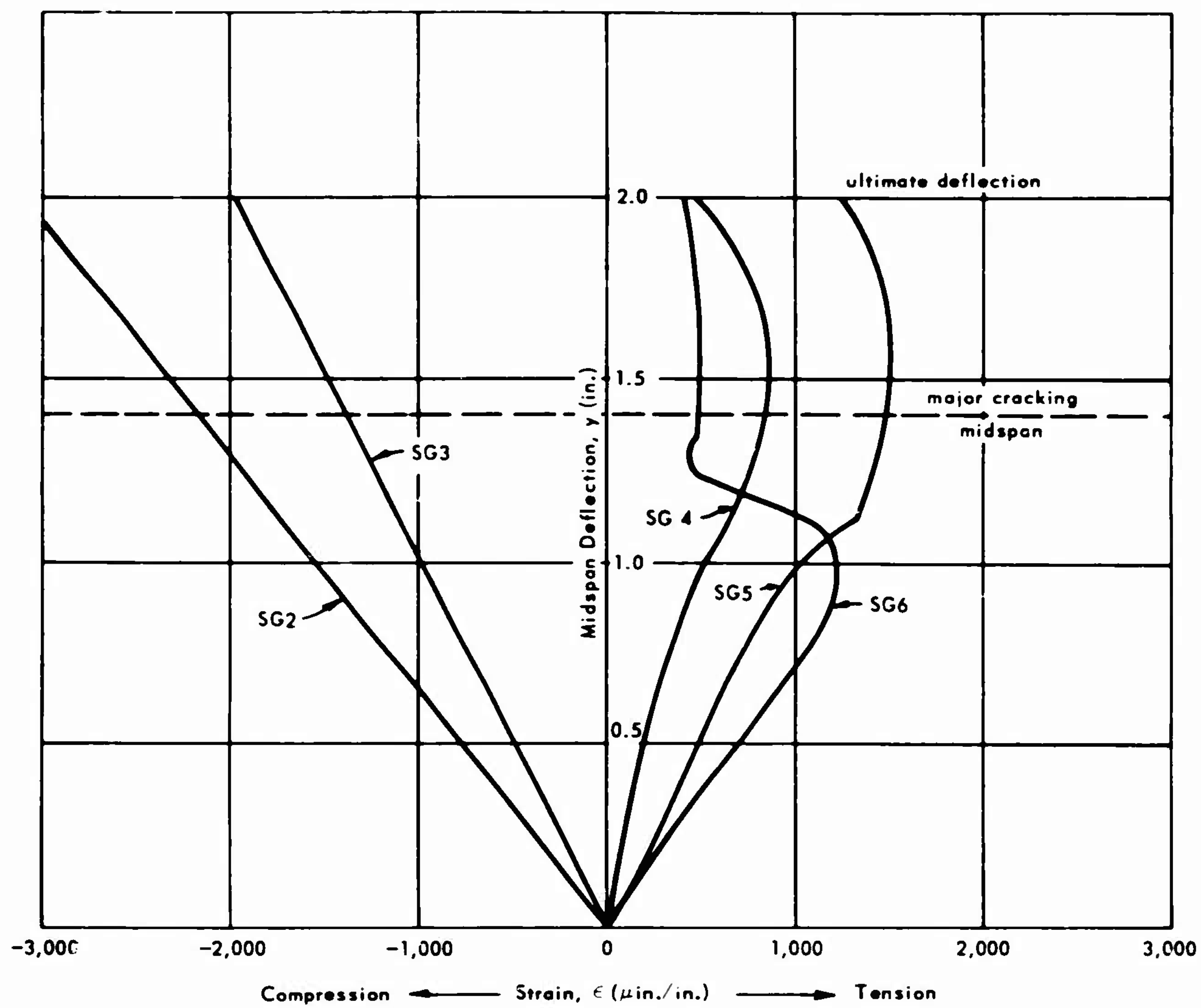


Figure A-4. Static strain-deflection curves, beam T6.

Appendix B

ANALYSIS OF MEMBERS

BEAMS

Previous experience has shown that the modulus of elasticity in compression for Douglas fir is not appreciably different from that in tension; therefore, the assumption that plane sections before loading remain plane in the deflected beam can be used.[18] It has also been experienced that the compressive flexural-yield stress is nearly approximated by the compressive stress parallel to the grain in standard compression tests.[18] No conclusive data are available on the pure tensile-yield strength of wood, but it is generally accepted that it is much higher than the compressive stress parallel to the grain.[18] A tensile failure usually occurs in flexural tests after considerable yielding in compression has taken place. Because the flexural-tension stresses increase nearly linearly up to the yield value, the ultimate resistance of the cross section can be approximated from a stress-block distribution (Figure B-1) similar to that in concrete. F om a summation of horizontal forces and moments at a cross section,

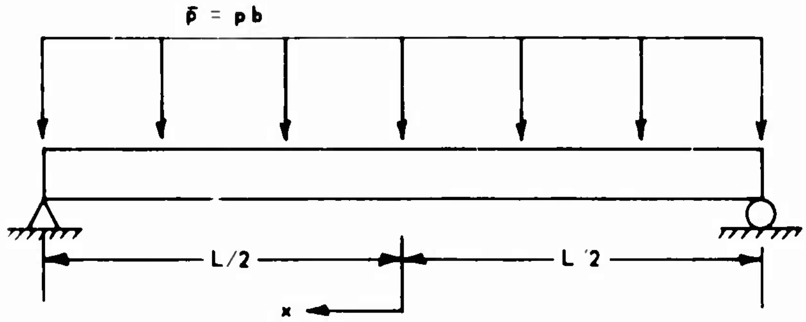
$$h = \frac{2S_c d}{S_c + S_t} \tag{B-1}$$

$$a = \frac{S_t}{S_c + S_t} h = \frac{2S_c S_t d}{(S_c + S_t)^2} \tag{B-2}$$

and

$$M_i = S_c b d^2 \left[\frac{1}{2} - \frac{2S_c}{3(S_c + S_t)} \right] = \text{internal moment at the cross section} \tag{B-3}$$

where the terminology is defined in Figure B-1. The total deflection in beams will be a result of flexural deflections combined with deflections due to shear. Established values for the shear modulus are not well defined, but can be determined experimentally. In the uniformly loaded beam shown below, the shear deflection and flexural deflections are given by the following equations:



$$\Delta_v = \int_0^L \frac{V v\,dx}{AG} = \frac{2}{AG}\int_0^{L/2} (\bar{p}x)\,\frac{1}{2}\,dx = \frac{\bar{p}L^2}{8AG} \tag{B-4}$$

$$\Delta_f = \frac{5\bar{p}L^4}{384EI} \tag{B-5}$$

where V = the shear at any location caused by ı e uniformly distributed loading

v = the shear at any location caused by a unit load applied at midspan

E = the modulus of elasticity

G = the shear modulus of elasticity

I = the moment of inertia of the beam cross section

A = the cross-sectional area

The total deflection is then found as

$$\Delta_t = \Delta_v + \Delta_f = \frac{pL^2}{8Gd} + \frac{5pL^4}{32Ed^3}$$

or

$$\Delta_t = \frac{pL^2}{32Ed}\left(\frac{4}{k} + \frac{5L^2}{d^2}\right) \tag{B-6}$$

where G = kE.

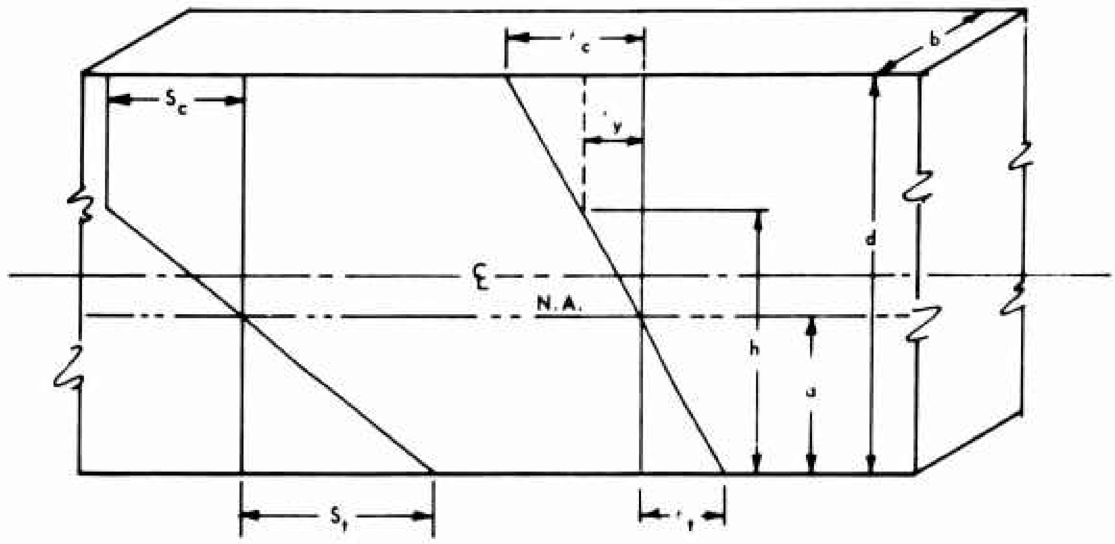


Figure B-1. Stress-strain distribution for timber in flexure past the proportional limit.

The ratio of shear deflection to flexural deflection is

$$\frac{\Delta_v}{\Delta_f} = \frac{pL^2}{8Gd}\left(\frac{32Ed^3}{5pL^4}\right) = \frac{4d^2}{5kL^2} \tag{B-7}$$

The quantity k can be determined from Equation B-6 as

$$k = \frac{4}{\dfrac{32Ed\Delta_t}{pL^2} - \dfrac{5L^2}{d^2}} = \frac{4D}{E\Delta_t - DF} \tag{B-8}$$

where

$$D = \frac{pL^2}{32d} \quad \text{and} \quad F = \frac{5L^2}{d^2} \tag{B-9}$$

The modulus of elasticity, E, can be determined in the elastic range from the applied loading and the measured flexural strain at midspan where the shearing strains are essentially zero:

$$E = \frac{3pL^2}{4d^2\epsilon} \quad \text{(B-10)}$$

Values of E, k, S_c, S_t, and M_i were computed using the data from the static tests to determine the relative deflection due to shear and to compare the value of the internal bending moment calculated from Equation B-3 with the applied bending moment calculated from statics. The value of S_c used in Equation B-3 for the internal bending moment was taken as the maximum fiber stress at the proportional limit (see Table 1). The maximum tensile stress, S_t, was calculated as the strain at ultimate load multiplied by the modulus of elasticity. Results of these computations are shown in Table B-1. This analytical approach is recommended in Reference 19.

PLYWOOD IN SHEAR

A shearing load acting lengthwise on a rectangular plywood panel can be treated as a force, the line of action of which coincides with the long axis of the top edge while the bottom edge remains in a fixed position. The deformations at a point within the panel are shown in exaggerated proportions by the dashed line in Figure B-2.

Shearing stress, τ, is given by

$$\tau = \frac{v}{t} \quad \text{(B-11)}$$

where v is the shearing force per inch of length at the boundary edge of the element, and t is the thickness of the panel. By definition,

$$G = \frac{\tau}{\gamma} \quad \text{(B-12)}$$

where G is the shear modulus of elasticity and γ is the shear strain.

Unit axial strains measured along the diagonals can easily be converted to shear strains by the use of Mohr's circle for strains. The angle between the measured strain, ϵ, and the shear strain, γ, is $\pi/4$; therefore,

$$\gamma = 2\epsilon \quad \text{(B-13)}$$

and

$$G = \frac{v}{2t\epsilon} \quad \text{(B-14)}$$

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Table B-1. Mechanical Properties of Beams in Fle

Beam	Elastic Range (20 psi)								
	Deflection (in.)	Strain (μ in./in.)	Modulus of Elasticity (10^6 psi)		k	$\frac{\Delta_v}{\Delta_t}$	S_c (psi)	ϵ_t (μ in./in.)	S (p
			Approximate	Revised					
U3	0.635	1,200	1.75	2.08	0.029	0.142	4,300	3,300	6,
U4	0.600	1,200	1.83	2.08	0.047	0.092	3,440	2,600	5,
T1	0.725	1,300	1.54	1.92	0.021	0.188	2,840	2,320	4,
T6	0.695	1,300	1.61	1.92	0.027	0.153	2,920	3,000	5,

e B-1. Mechanical Properties of Beams in Flexure and Shear

)			Ultimate Load					
	k	$\frac{\Delta_v}{\Delta_t}$	S_c (psi)	ϵ_t (μ in./in.)	S_t (psi)	Moment (10^6 in.-lb)		
evised						Theoretical	Experimental	Experimental Theoretical
2.08	0.029	0.142	4,300	3,300	6,900	1.381	1.670	1.20
2.08	0.047	0.092	3,440	2,600	5,400	1.084	1.168	1.07
1.92	0.021	0.188	2,840	2,320	4,460	0.899	1.000	1.11
1.92	0.027	0.153	2,920	3,000	5,760	1.060	1.00	0.95

R

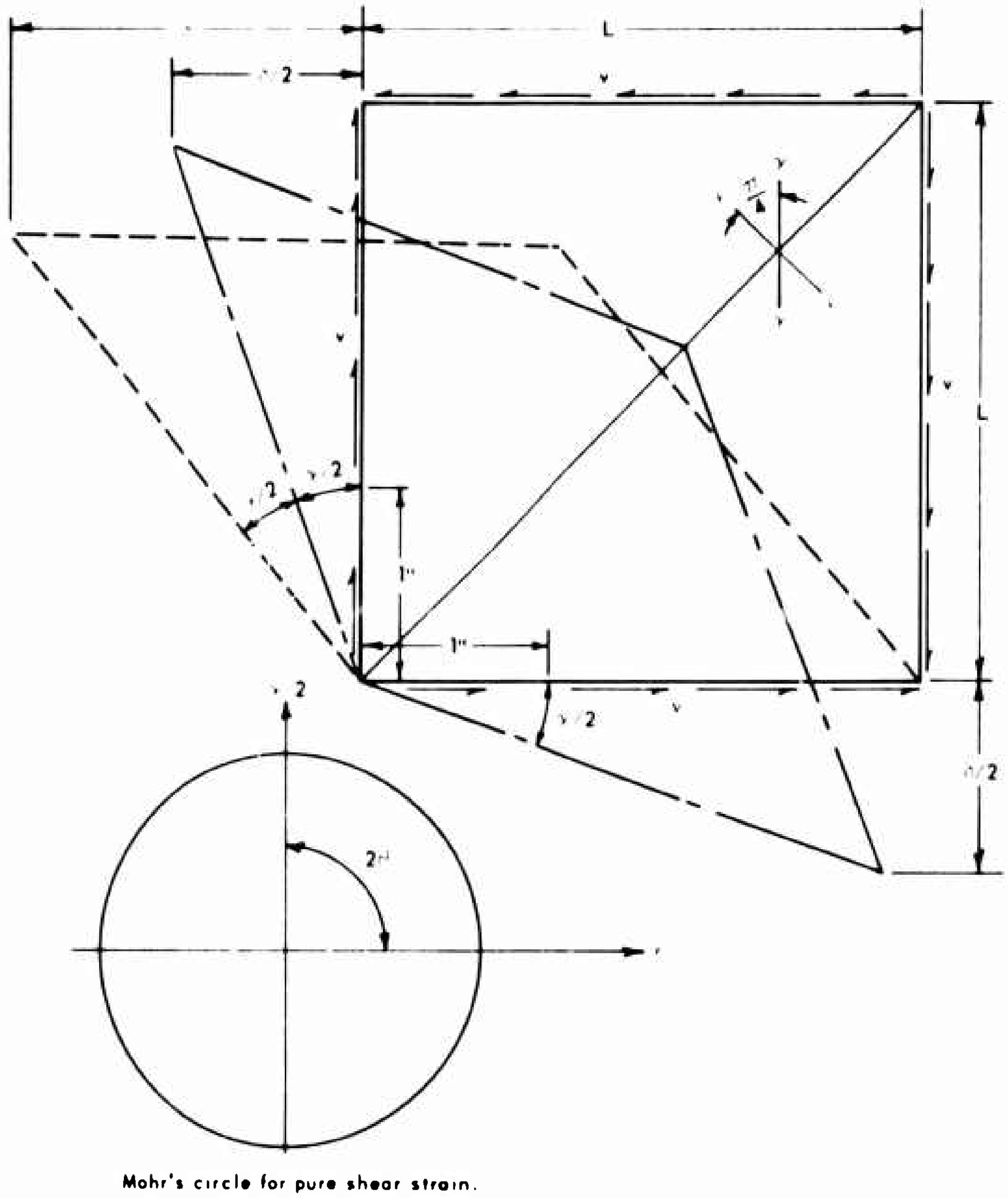


Figure B-2. Deformation of plywood subjected to pure shear strain.

The analysis is unchanged if the deformed shape is rotated an angle $\gamma/2$. In this case the slope of the diagonal does not change, and the resulting elastic equations are identical to Equations B-11 through B-14.

Appendix C

EXPERIMENTAL RESPONSE CURVES FOR DYNAMIC TESTS

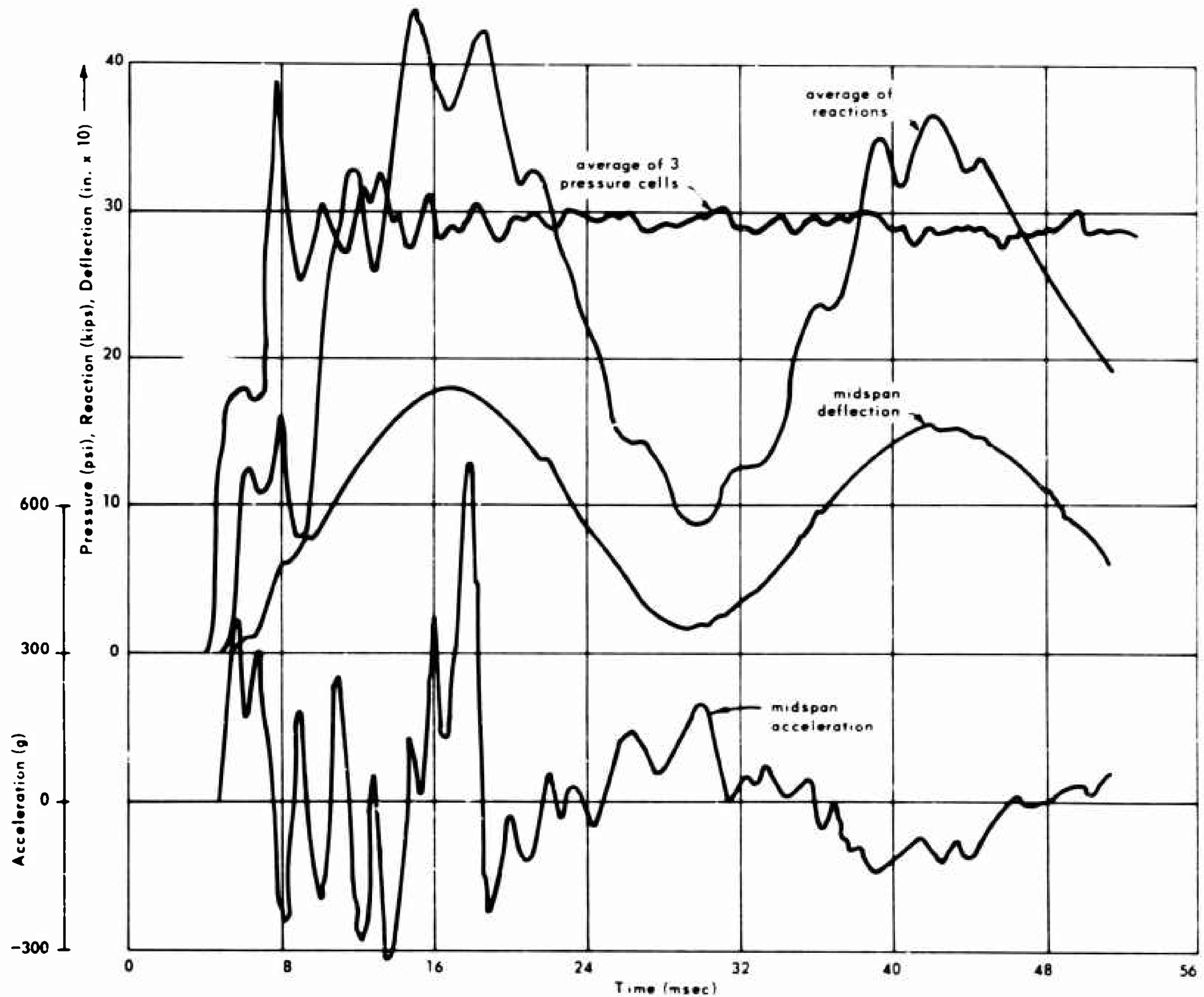


Figure C-1. Response to blast loading, beam U3(1).

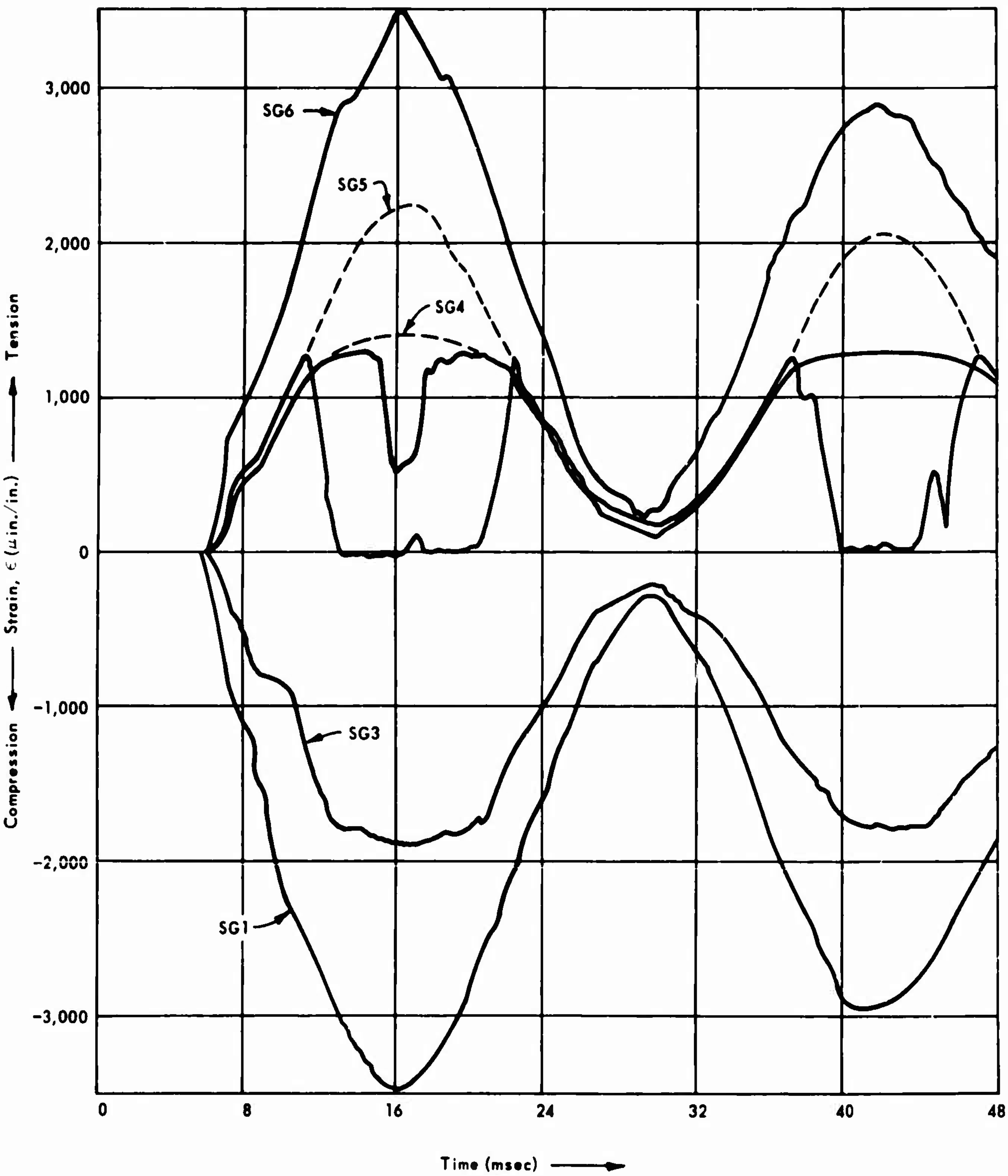


Figure C-2. Strain-gage data, beam U3(1).

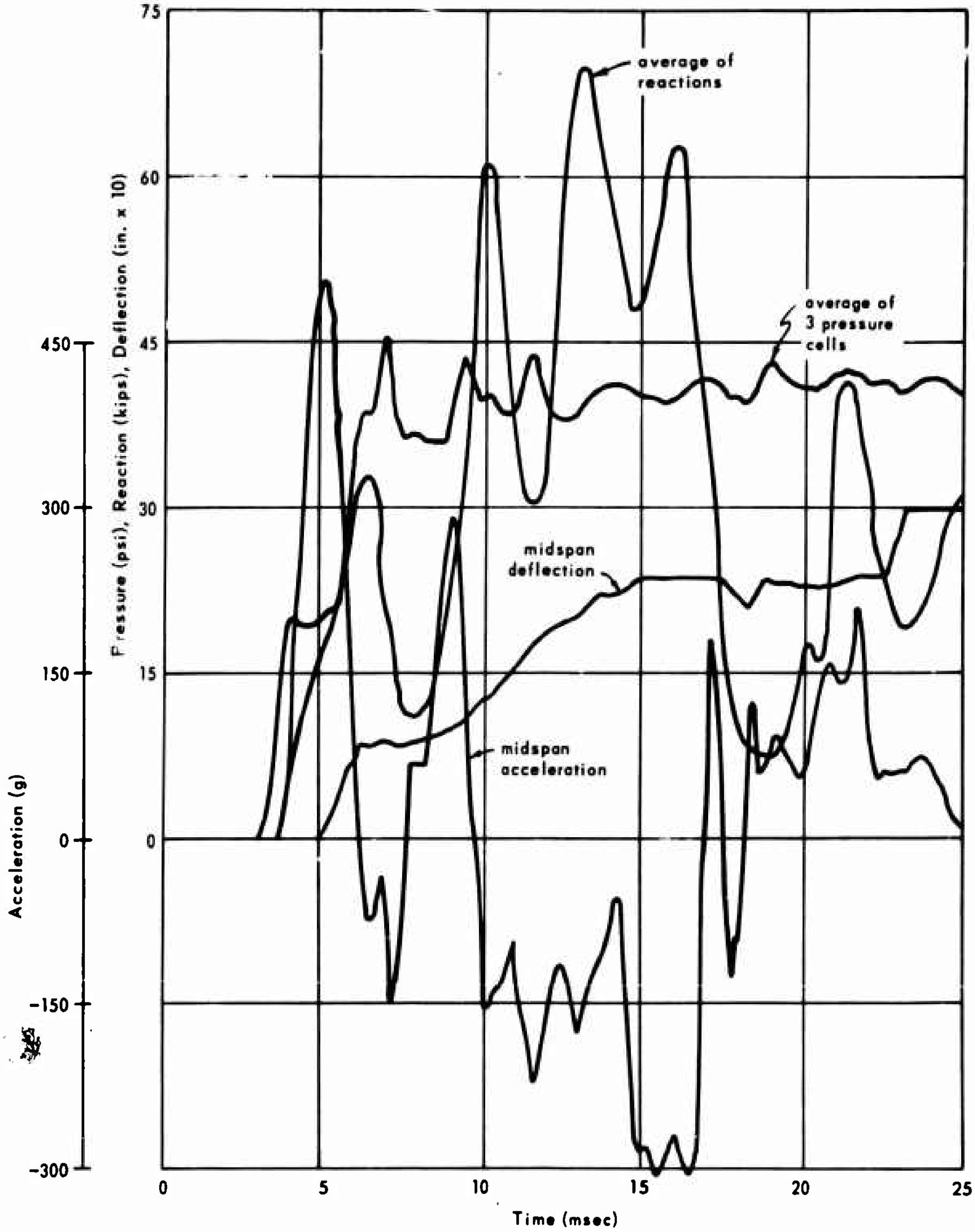


Figure C-3. Response to blast loading, beam U5(2).

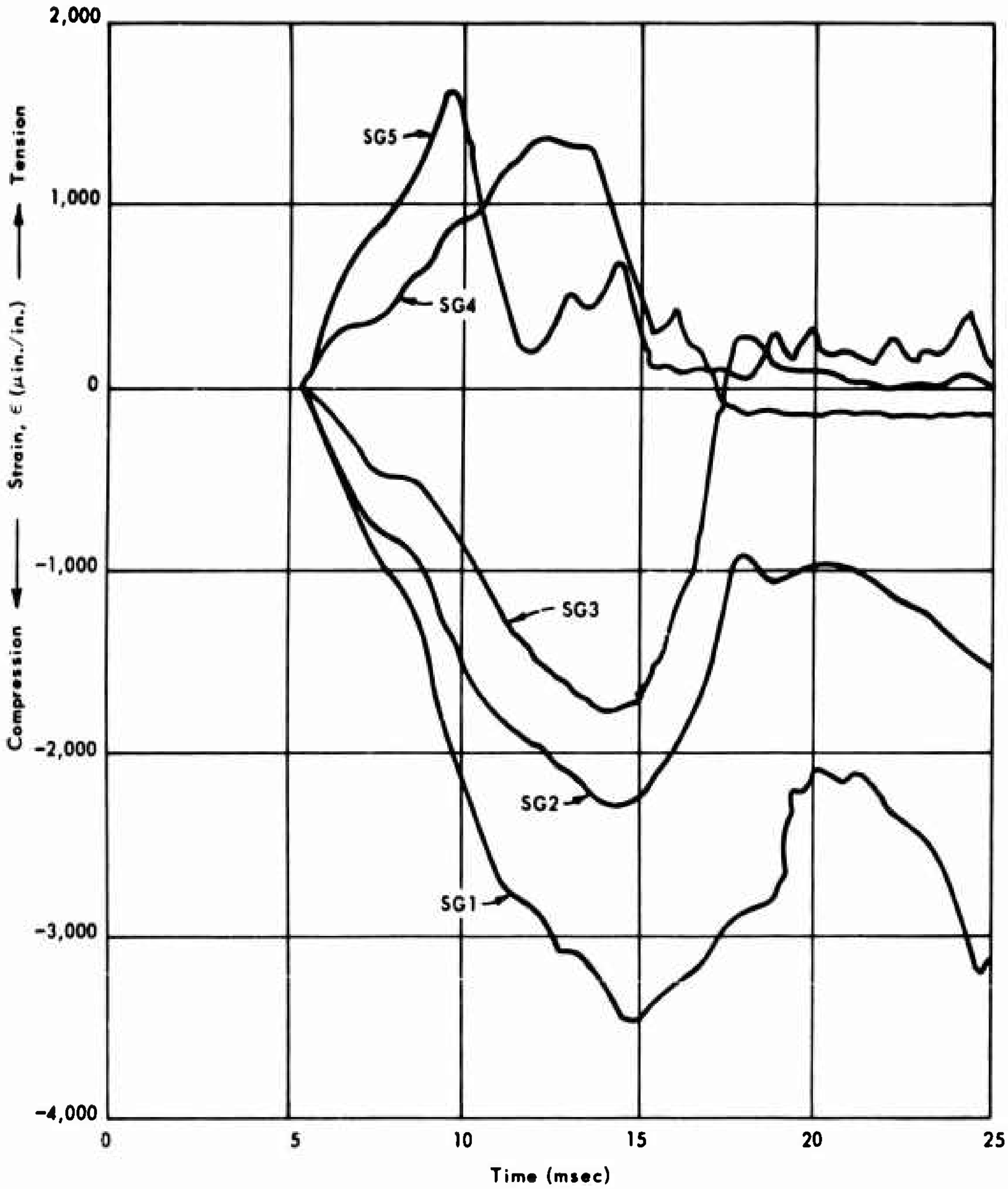


Figure C-4. Strain-gage data, beam U5(2).

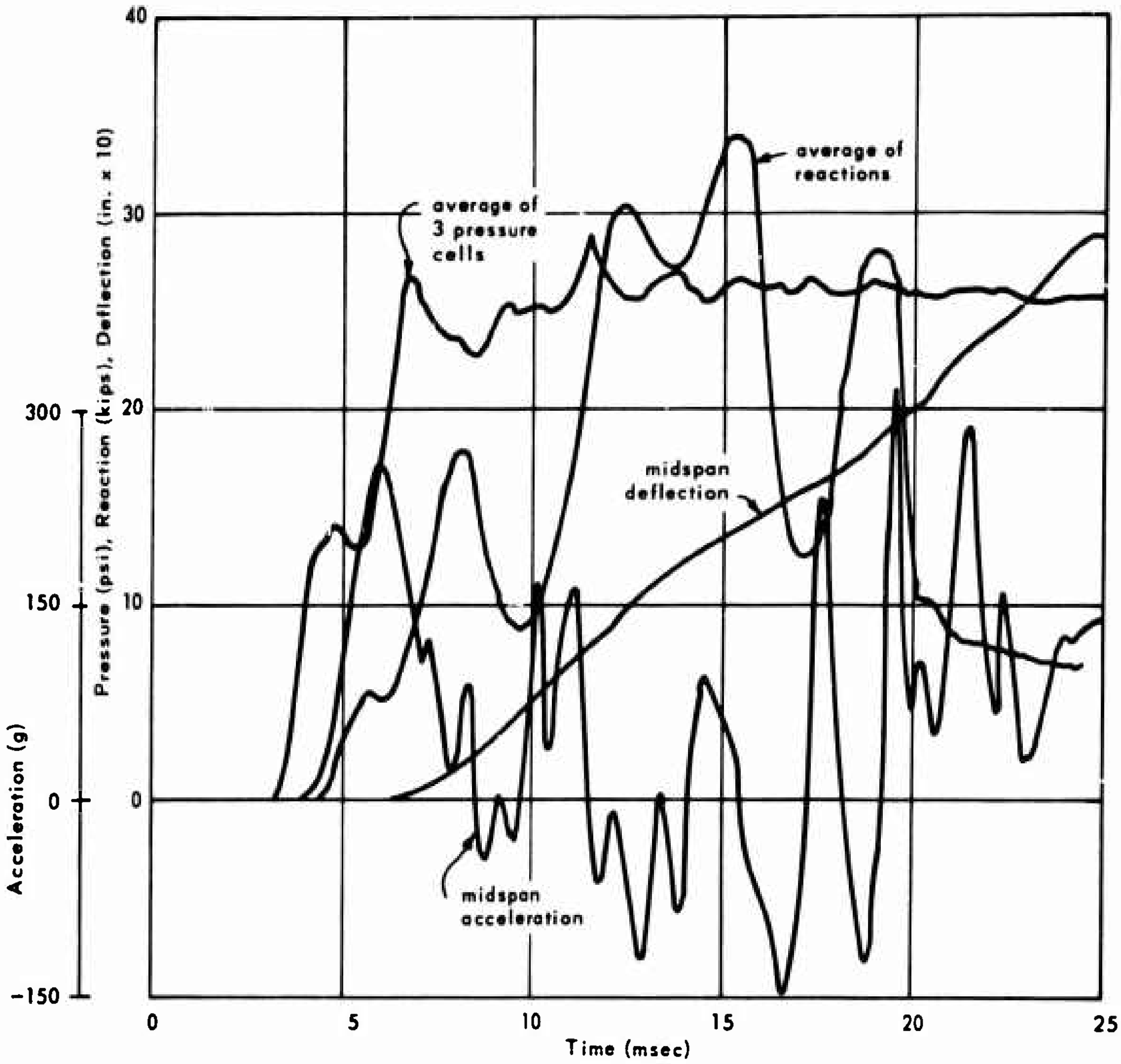


Figure C-5. Response to blast loading, beam T3.

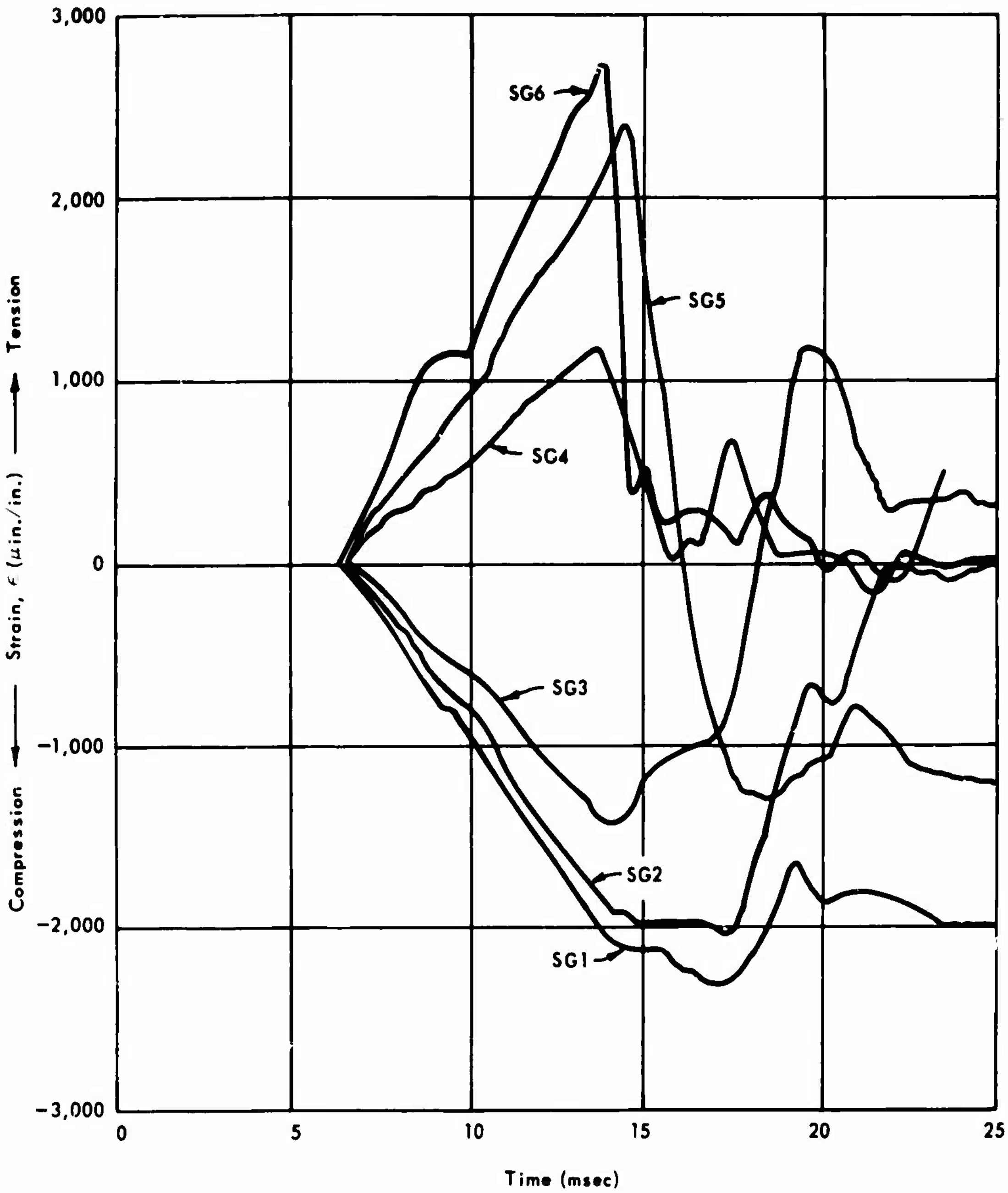


Figure C-6. Strain-gage data, beam T3.

Appendix D

MOISTURE CONTENT AND SALT PENETRATION

The weight of each beam and plywood sheet before treatment could not be obtained; therefore, exact values for moisture content and salt retention in terms of the weight of the dry wood could not be determined. The approach used was to assume that the oven-dried weight of the wood was the same in all beams and that the dry wood in each half panel of an original plywood sheet was the same; calculations are then based on the average dry weight of the untreated beams and plywood sheets. This assumption proved reasonable, because the maximum variation between beams was only about 6%.

A 30-inch-long section was cut from each beam near midspan to determine the oven-dry weight of the wood in the untreated beams and the combined weight of wood plus salt in the treated beams. The weight of salt in each treated section was taken as the difference between the weight of the oven-dried treated section and the average of the oven-dried untreated sections. The results of these calculations for the beams are shown in Table D-1. Computations for the plywood sheets were similar, and the results are presented in Table D-2. Formulas used in the computations are given in Tables D-1 and D-2.

Penetration of the salts at cross sections near midspan of the treated beams is shown in Figure D-1. The penetration patterns were quite irregular and changed with the position along the axis of the beam.

Table D-1. Moisture Content and Salt Content in Laminated Beams

Beam	Initial Weight (lb)	Test Weight (lb)	Oven-Dry 1/ Weight (lb)	Moisture 2/ at Test (%)	Salt 3/ Weight (lb)	Salt 4/ Content (%)
U1	355	355	339	4.7	-	-
U2	375	375	363	3.3	-	-
U3	353	353	338	4.4	-	-
U4	357	357	342	4.4	-	-
U5	380	380	353	7.6	-	-
U6	351	351	321	9.3	-	-
Avg			342 (±6%)			
T1	625	576	440	39.8	98	28.7
T2	581	538	401	40.1	59	17.3
T3	627	568	411	45.9	69	20.2
T4	618	561	404	45.9	62	18.1
T5	622	560	435	36.5	93	27.2
T6	590	482	400	24.0	58	17.0

1/ Dried at 217°F until a constant weight was reached.

2/ For untreated beams: $\frac{\text{(test weight)} - \text{(oven-dry weight)}}{\text{oven-dry weight}}$.

For treated beams: $\frac{\text{(test weight)} - \text{(oven-dry weight)}}{342}$.

3/ Oven-dry weight - 342.

4/ $\frac{\text{salt weight}}{342}$.

Table D-2. Moisture Content and Salt Content in Plywood Specimens

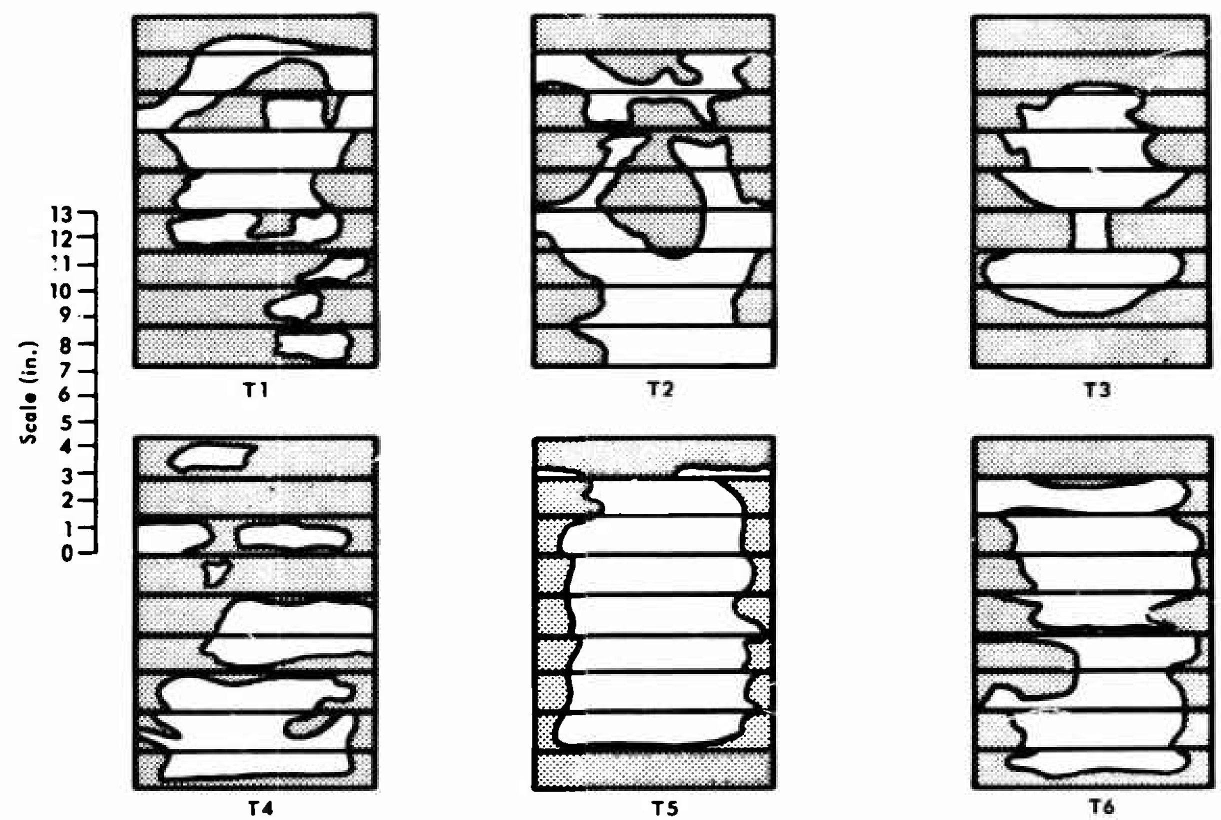
Specimen	Wet Weight (gm)	Oven-Dry 1/ Weight (gm)	Salt 2/ (%)	Moisture 3/ (%)
Treated panel A	1,995	1,841	19.2	10.3
Untreated panel A	1,676	1,544	0	8.5
AT-1	512	473	19.2	10.2
AT-1 control	443	411	0	7.8
AT-2	435	402	19.2	10.1
AT-2 control	405	376	0	7.7
Treated panel B	1,766	1,636	16.5	9.5
Untreated panel B	1,500	1,404	0	6.8
BT	403	366	16.5	12.1
BT control	748	699	0	7.0
BT-1	360	331	16.5	10.5
BT-1 control	413	385	0	7.3
BT-2	435	404	16.5	9.2
BT-2 control	363	339	0	7.1
Treated panel C	1,896	1,757	10.6	8.8
Untreated panel C	1,692	1,588	0	6.5
CT	454	413	10.6	11.1
CT control	404	374	0	8.0
CT-1	960	890	10.6	8.8
CT-1 control	394	372	0	5.9
CT-2	481	446	10.6	8.8
CT-2 control	442	420	0	5.2

1/ Dried at 217°F for 48 hours.

2/ Determined from:

$$\frac{\text{(oven-dry weight of treated panel)} - \text{(oven-dry weight of untreated panel)}}{\text{oven-dry weight of untreated panel}} \times 100$$

3/ Determined from: $$\frac{\text{(wet weight)} - \text{(oven-dry weight)}}{\text{(oven-dry weight)}\left(1 - \frac{\%\ \text{salt}}{100}\right)} \times 100$$



Note:
Shaded portion indicates penetration.

Figure D-1. Depth of penetration of salts near midspan.

Appendix E

PHOTOGRAPHS OF BEAMS AFTER TEST

Figure E-1. Post shot view of beams U1, U2, and U3(2).

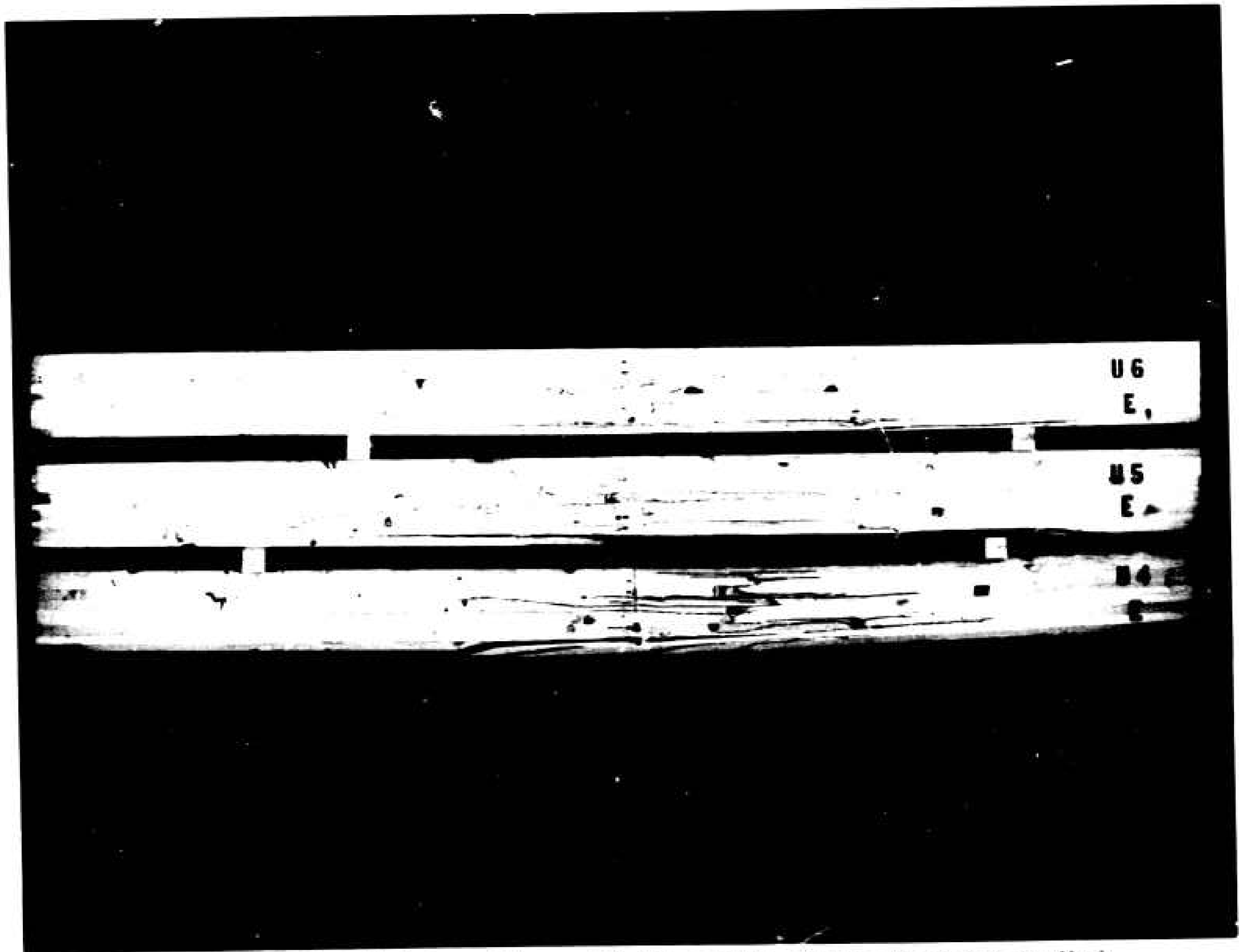


Figure E-2. Post shot view of beams U4, U5, and U6. (U4 was loaded statically.)

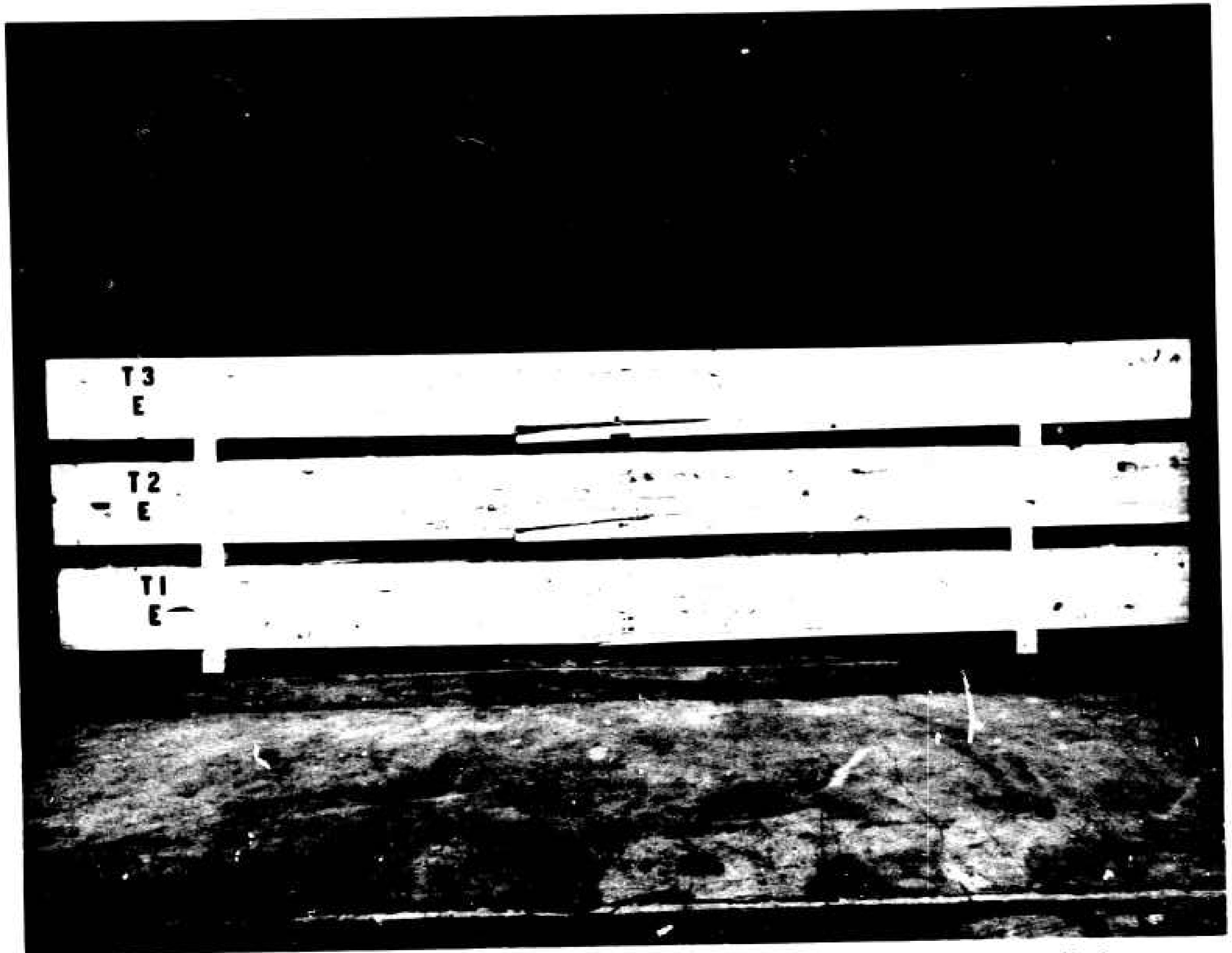


Figure E-3. Post shot view of beams T1, T2, and T3. (T1 was loaded statically.)

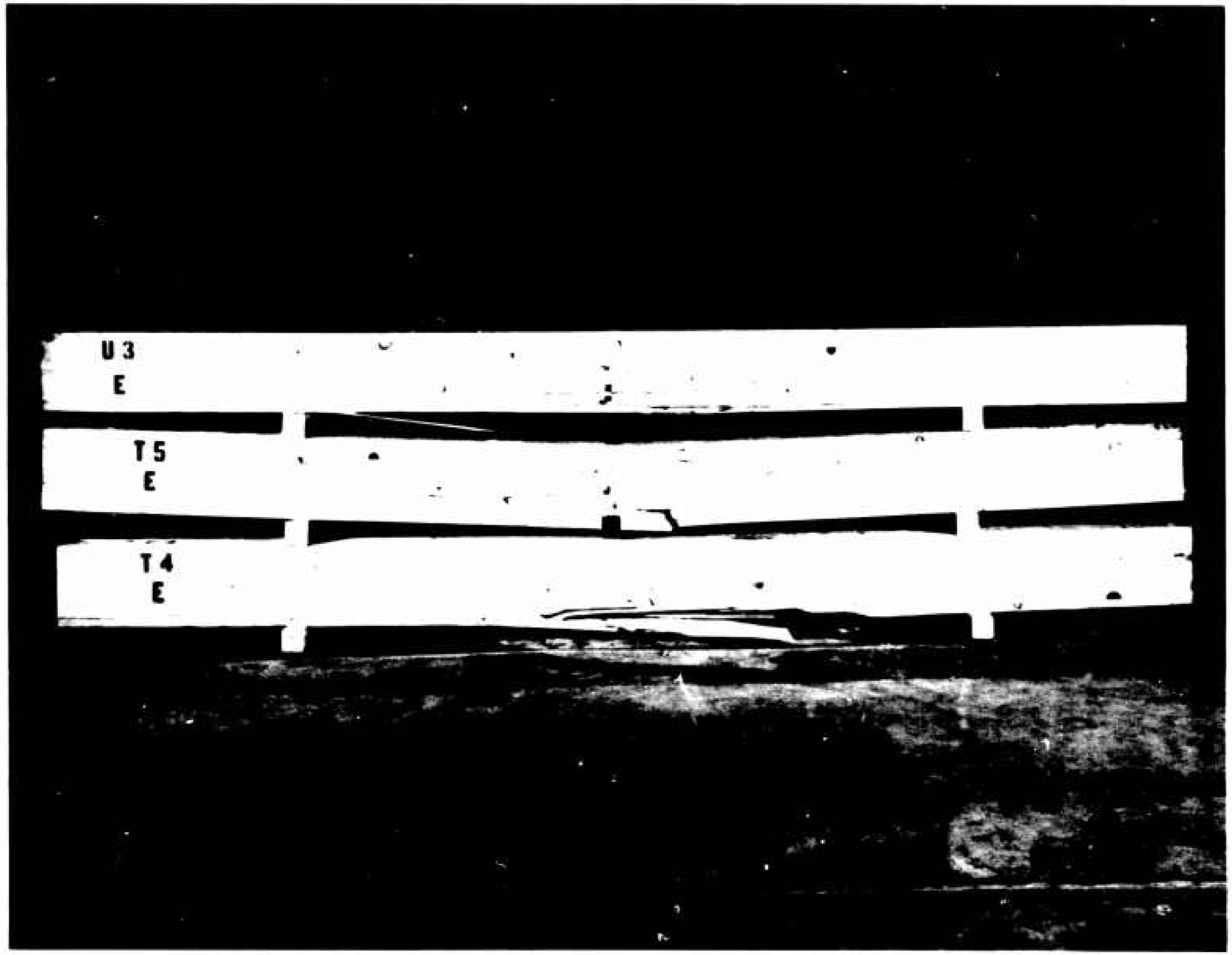


Figure E-4. Post shot view of beams T4, T5, and U3. (U3 was loaded statically.)

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13. ABSTRACT

A series of treated and untreated laminated Douglas fir beams and plywood panels were subjected to static and dynamic loads to study the effects of pressure-impregnation with fire-retardant chemicals on the mechanical properties of wood and to extend the existing knowledge of the dynamic properties of wood.

Results from the beam tests indicate that designs should be based on use under wet conditions when large timbers are to be pressure-impregnated with fire-retardant chemicals; this is because of the hygroscopic nature of treated lumber. It was also found that the allowable static design load can be applied dynamically without damage to the beam. Ultimate resistance of dry untreated beams to dynamic loads was about 1.6 times the allowable design load for dry wood; for treated beams, the ultimate resistance to dynamic loads was about 1.4 times the allowable design load for wet lumber.

Results from the plywood shear tests indicate that fire-retardant treatments reduce the mechanical properties of plywood in shear and that the reduction is proportional to the amount of salt retained in the wood.

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